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The Grasping Hand

Christine L. MacKenzie
Thea Iberall

North-Holland

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THE GRASPING HAND

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Preface

In the summer of 1985, at a Motor Control conference in Henniker, New Hampshire, we met and discovered another individual who shared a fascination (some might say obsession!) about the human hand. Together, we marvelled at its versatility and its multipurpose functionality, and discussed the control problem for dextrous hands from biological and computational perspectives. But at the same time, we were astounded by the lack of a coherent, integrative framework dealing with the hand's complexities. A common vocabulary was lacking for workers in different disciplines; pockets of research existed, without overall context. Immediately we saw the need for a book to bring together knowledge about the hand from these diverse perspectives. With complementary backgrounds in computing science and computer engineering (TI) and kinesiology (CM), we were challenged to integrate the current works on the hand.

The ultimate goal of this book is to identify the underlying functionality of the human hand in prehension. We address two questions: the question of what is the nature of the human hand and the question of what might be involved in the CNS as it controls this marvelous tool in prehension. Our approach is based on the assumption that a complete model of grasping must be developed and validated both empirically and computationally. The approach is three-fold: we use behavioral evidence, biological data, and computational results to further develop and validate models of prehensile functions. In contrast to a reductionist approach, we focus on sensorimotor integration processes, which are more than the simple sum of the motor and the sensory components.

The significance of such a book is to provide a study of prehension that is comprehensible to interdisciplinary and multidisciplinary researchers. Designers of prosthetic and robotic dextrous hands will find this study useful for developing versatile end effectors. Practitioners of hand rehabilitation will also gain insights for improving functionality in injured hands. To motor psychologists, neurophysiologists, and kinesiologists, we offer many testable hypotheses, which we feel can be verified through experiments. For computational modellers, we provide suggestions for critical inputs and outputs, identifying areas for future work. Another use is as a textbook for senior undergraduate and graduate level seminars in diverse fields, including computational neural modelling, motor control, and cognitive science.

We acknowledge the growing interest and interdisciplinary research into human hand movement. The need for a common vocabulary has been obvious at major symposia and conferences. For example, the Canadian Institute for Advanced Research (CIAR) sponsored a special workshop in London, Canada in May, 1987, bringing together experts in robotics, artificial intelligence, and human movement science to share their approaches to prehension (see Goodale, 1990). Another example was the Dextrous Robot Hand Workshop in Philadelphia, U.S.A. in April, 1988, at the IEEE Conference on Robotics and Automation (see Venkataraman and Iberall, 1990). In both locales, the enthusiastic discussions and realization of common concerns and goals were offset by the lack of an integrative framework. Other recent meetings on Hand Function occurred in Montreal, Canada in May, 1993 and in Ascona, Switzerland in March, 1994.

We are coauthors in the complete sense: neither one of us alone could have written this book. Over the last 7 years we have met together annually, travelling some distance to update this work. One baby was born, two moves were made from the East to the West coast of North America, each of us has moved to a new university, and made other major life changes.

We hope that this book will facilitate effective communication, and make a contribution toward advancing knowledge on human prehension.

Acknowledgements

Many individuals have contributed to this work in many ways. Thanks to our teachers and mentors, both formal and informal. Graduate courses were offered at the University of Southern California and the University of Waterloo, based on earlier drafts of **The Grasping Hand,** and we had lively discussions with colleagues also at Simon Fraser University. We wish to thank our students, teachers and colleagues for enriching both the seminars and the book. Thanks to the following individuals for providing feedback on earlier queries or drafts of the manuscript: Fran Allard, Michael Arbib, Denise Beattie, George Bekey, Reinoud Bootsma, Phil Bryden, Heather Carnahan, Sheril Desjardins-Denault, Marcus Devanandan, Virginia Diggles, Claude Dugas, Andy Fagg, Ken Goldberg, Evan Graham, Suzanne Halliday, Bruce Hoff, Marc Jeannerod, Linda Kalbfleisch, Susan Lederman, Gary Lindquist, Ron Marteniuk, Sean Maw, Chris McManus, John Medley, Ted Milner, Jacques Paillard, Shahram Payendah, Don Ranney, Eleanor Robbins, Marg Savage, Barb Sivak, S.T. Venkataraman, Patricia Weir, Richard Wells, Evelyn Yeo, and Ruth Zemke. For any oversights, we offer our apologies and thanks.

Thank you to Nikos Apostolopoulos, Elizabeth Carefoot, and Kathleen Maraj for contributing artwork and graphics, and to Ron Long and Greg Ehlers for their photographic expertise. Special thanks to Evelyn Yeo, who, as a summer research student at Simon Fraser University, cheerfully and competently assisted in compiling references and figures, and provided model hands. All these individuals helped to add the aesthetic dimension we wanted.

We wish to acknowledge the support and working environment of the Departments of Kinesiology and Computer Science at the University of Waterloo, where this work was initiated. With moves to the West Coast, we wish to acknowledge at Simon Fraser University the support of the School of Kinesiology, Centre for Systems Science, and Instructional Media Centre, and at the University of Southern California, the Department of Computer Science.

Publishing this work in the Advances in Psychology Series published by Elsevier Science is, for us, an honor and we wish to thank George Stelmach and Kees Michielsen for their support and encouragement.

Finally, all our love and thanks to our families and friends for their faith and for "hanging in" for the seven year period we have been working on this book. This book was conceived around the same time as Anne MacKenzie Marteniuk, who at a joyful six years of age, kept us going at the end with hand poems and drawings. Christie expresses her love and thanks to Anne and Ron Marteniuk for their support and patience with "the same time next year" routine. Thea thanks her parents, sisters, friends, and god for their continued support, love, and patience.

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Part I

WHAT IS PREHENSION?

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Chapter 1. Introduction

"But between the mind and the hand the relationship is not so simple as that of a master to a humble servant...Gestures may continually reflect the inner feelings. (Conversely,) hands have their gifts inscribed in their very shape and design...The mind makes the hand, the hand makes the mind."

--H. Focillon (1947)

grasp: *v.t.* 1. to seize and hold by clasping or embracing with the fingers or arms. 2. to take hold of eagerly or greedily; seize. 3. to seize mentally; to comprehend; as, to grasp the question. *n.* 1. the grip or seizure of the hand. 2. possession; hold. 3. reach; the power of seizing. 4. understanding; comprehension; intellectual capacity. 5. the part of a thing to be held or grasped, as the grasp of a sword or of a fishing rod. From the ME. *graspen, grapen, grapien,* from AS. *grapian,* to grasp. (Webster's New Twentieth Century Unabridged Dictionary, 2nd Edition.)

prehension: *n.* 1. a taking hold; a seizing, as with the hand or other limb. 2. mental apprehension. From the Latin *prehendere,* to take or seize. (Webster's New Twentieth Century Unabridged Dictionary, 2nd Edition.)

What do human hands do? Look around you. All around are examples of the power of the human hand: the construction of buildings, the designing of furniture, the intricacy of tool design, the taming of electricity. No animal on Earth shapes its world as much as we do. Not only can we envision the process of fabrication, but we can also implement those designs, through the power of the brain working together with the human hand.

The human hand is a highly complex structure that in many ways defies understanding. Questions abound as to whether its beauty comes from its own internal architecture or else from its controller, the human central nervous system (CNS). As the famed surgeon Frederick Wood-Jones (1920) said, "The difference between the hand of a man and the hand of a monkey lies not so much in the movements which the arrangement of muscles, bones and joints make possible... but in the purposive volitional movements which under ordinary circumstances the animal habitually exercises."

The hand itself consists of five digits made up of a collection of bones, muscles, ligaments, tendons, fascia, and vascular structures encapsulated by skin. Thousands of sensors in the skin, muscles, and joints let the brain know its current state. Yet, what are the functions supported by that form? The hand of *Homo sapiens sapiens* represents millions of years of evolutionary pressures and changes. These changes both allowed and necessitated the use of tools: the remodelling of the hand (e.g., shorter fingers, nails instead of claws) enabled the hand to grasp stones, bones, and wood, and to modify them into functionally effective tools; but, the remodelling of the hand into a general purpose prehensile device also created a need for those tools. Tools became an extension of the hand. Without tools, the hand is limited in strength and precision; with tools, the hand can either be enhanced in its power (as with a wrench) or in its precision (as with a fine screwdriver or needle). If it is the brain that is envisioning the process, then the hand is an extension of the mind.

We use our hands, as general purpose devices, to pick up objects, to point, to climb, to play musical instruments, to draw and sculpt, to communicate, to touch and feel, and to explore the world. One need only examine a number of skills to discover many of the functional postures that the hand can adopt. When a person reaches out to grasp an object, the hand opens into some suitable shape for grasping and manipulation - suitable, in the sense that the person's understanding of the task influences the shape of the hand. For example, when grasping a coffee mug by the handle, the index finger (and maybe other fingers) extends to grasp the handle; the other fingers curl up against the palm. The finger pads are used to make contact with the handle, and then the fingers move along the surface, establishing a stable grasp. Though invisible, complex adjustments of the fingers are made in order to maintain a stable grasp, even while holding the mug. If one is picking up the mug to drink, the size of the handle constrains the grasp. One finger fits a teacup handle, four a beer stein. As well, the hand posture adapted for drinking is dramatically different from that used to throw the mug at someone else.

Some skills require that an object is grasped in order to act upon another object. We use a screwdriver to tighten a screw into the wall because using our hands directly would not be as effective. Of course, under the pressure of finishing a job when the proper tools are not available, we can use our hands (see Figure 1.1). First, grasping the screw between our index finger and thumb tips, we insert the screw into the hole and rotate it as we would if we were using a screwdriver. Then, when the screw head gets too close to the wall to

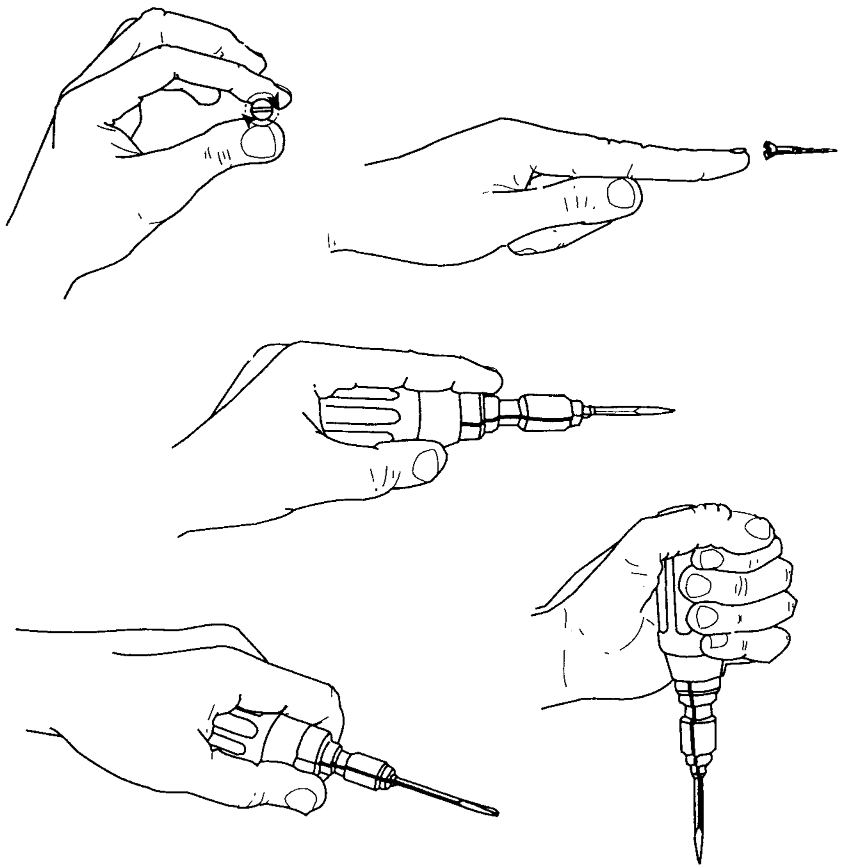

Figure 1.1 Examples of prehension, using the hand alone and with a tool. Without a screwdriver, one might use the thumb and index finger to turn a screw. As the screw head gets close to the surface, the index fingernail is inserted for the last few turns. When a screwdriver is handy, it is grasped in a way to tighten a screw. Note the different, functional hand postures used for grasping the same screwdriver to open a paint can or mix the paint.

continue in this way, we modify our hand shape and insert the index fingernail into the screw slot, and rotate the hand, turning the screw in a way to get the job done adequately. Now, suppose the job were to paint the wall. We look around for an object to lever open the lid of the paint can, and perhaps all we see is a screwdriver. With its long shape to provide an effective lever and a thin end to fit under the lip of the lid, it will do the job. Then, with the paint can open, the paint must be stirred. Having misplaced our paint stirrer, we once again reach for our trusty screwdriver, which in a pinch also suffices for this activity!

In these activities, the hand shapes differently. While the screwdriver properties are not changing, the task is different in each case. The grasp chosen for levering and stirring no longer resembles the more standard way of grasping the screwdriver. And while the screwdriver's physical properties exist to support its primary function, those very properties can be used for other functions. The shape taken on by the hand for grasping the screwdriver in these other tasks reflects the needs of these secondary functions. Importantly, we see that the hand, as a general purpose tool, can shape itself into a posture suitable to perform a given function. This can be to grasp an object to do the function, or it can be to shape itself into a tool to perform that function directly. In fact, most tools are designed to simplify accomplishing the tasks previously done by the naked hands.

How do our brains control our hands? The brain, as a complex system, can be modelled using theories containing hypothetical explanations, suppositions, and conjectures. If we think in terms of a black box (see Figure 1.2), we can ask how such a system maps inputs into outputs. In this case, the question is how the hand is being controlled in prehensile behavior. The controller is the central nervous system (CNS) or perhaps even a computational control system. The hand could be a natural human hand or a dextrous prosthetic or robotic hand. Our working definition of prehension is *the application of functionally effective forces by the hand to an object for a task, given numerous constraints*[1]. The inputs to the black box are an object and a task. The output is prehensile behavior, measured as postures and forces unfolding over time.

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[1]Prehensile behavior can also be accomplished by tails, trunks, tongues, teeth, or other animal body parts. In this book, we have restricted our focus to the primate hand.

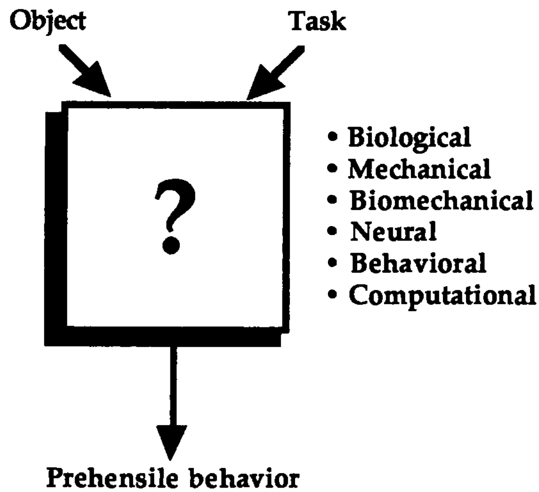

Figure 1.2 What is the problem that the controller solves? How does it solve it? What are techniques for answering these questions?

Empirical studies within fields such as psychology, kinesiology, and neuroscience, allow researchers to choose a set of measurable dependent variables and to see how they vary as a function of experimental manipulations. This allows inferences to be made about the internal operation of the black box of Figure 1.2 to either support or refute the various theories. One of the earliest systematic studies of rapid arm and finger movements was done by Robert Sessions Woodworth (1899) who described goal-directed movements as being two-phased: an initial, ungoverned motion followed by a final, controlled adjustment. In the first demonstration of accuracy-speed measurements, he showed that visually-guided slow movements were more accurate than fast ones or eyes-closed slow movements. These early experiments led to studies by other researchers that addressed questions such as: what is the role of sensory information; what are the different contributions of central and peripheral vision; how do we perceive task-related object properties; what happens if the target is moving; how are different grasps selected and effected; and how do we apply functionally effective forces. At the same time that the field of experimental psychology was emerging, physiological experiments were being conducted that began to shed light on the neural control of movement. Dominating the early work in this field, the physiologist Sir Charles Sherrington (1906) coined the term *proprioception* for the collective position sense stemming from sensors in the muscles, joints, and tendons. Ultimately, this work has led to questions such as: in what frame of reference do movements occur; how does automatic regulation of movement occur; what happens when different parts of the brain are lesioned; how are multiarticulate movements coordinated; and what are the dynamical characteristics of the limb. Today, these fields blend as tools and techniques for measurement and analyses become more sophisticated, and the complexity of the human body becomes realized.

In a similar vein, engineers, mathematicians, and computer and cognitive scientists design various forms of computational architectures that may allow a simulation of the mapping between inputs and outputs within the black box of Figure 1.2. These simulations have been designed using computational neural networks, artificial intelligence programming techniques, expert systems and even implemented mechanically in robotic systems. Struggling to develop robot controllers for systems working in unknown environments, roboticists address many of the same problems faced by researchers in motor behavior: how can a computer system coordinate multiple degree of freedom limbs as well as the brain does; how can sensors be designed and multiple modalities integrated; how is sensory information integrated with movement; how does stable grasping occur; how does movement occur in spite of the complex forces acting on the system; how are objects perceived; and how does planning occur.

Marr (1981) suggested three levels for analyzing systems that perform complex information processing. These are the task level, the representation or algorithmic level, and the implementation level. An example to demonstrate the distinctions is derived from flying. While both airplanes and birds fly, the algorithms they use are different: airplanes use jet propulsion while birds flap their wings. At the implementation level, airplanes use jets made out of materials such as steel, while birds use muscles and feathers. We will make similar distinctions in terms of prehension.

The close relationship between computational and experimental researchers is seen in Figure 1.3. Advances in science unfold through the interaction between theory and data. To start with, conceptual models are important for understanding complex systems and act to suggest experimental and computational models. Conceptual models are the theory part of science. They begin on a piece of paper (or a napkin!), and might leave out the details of how they might be implemented. Good conceptual models offer testable hypotheses that experimental results can support or refute. Platt (1964), in a powerful statement on the importance of strong inference as a way to further science, argues that the first question to ask on hearing a scientific theory is, 'But what experiment could disprove your hypothesis?' The power of empirical studies is that observations are made directly on the system of interest. Actual data are collected. Experiments can be designed with manipulations to perturb the system and/or to explore the range and boundary conditions for system behaviors at many levels of analysis. These experiments can be behavioral, anatomical, biomechanical, or neurophysiological. Behavioral studies allow one to observe behavior where a task is set up with constraints, and then to measure various aspects of the movement.

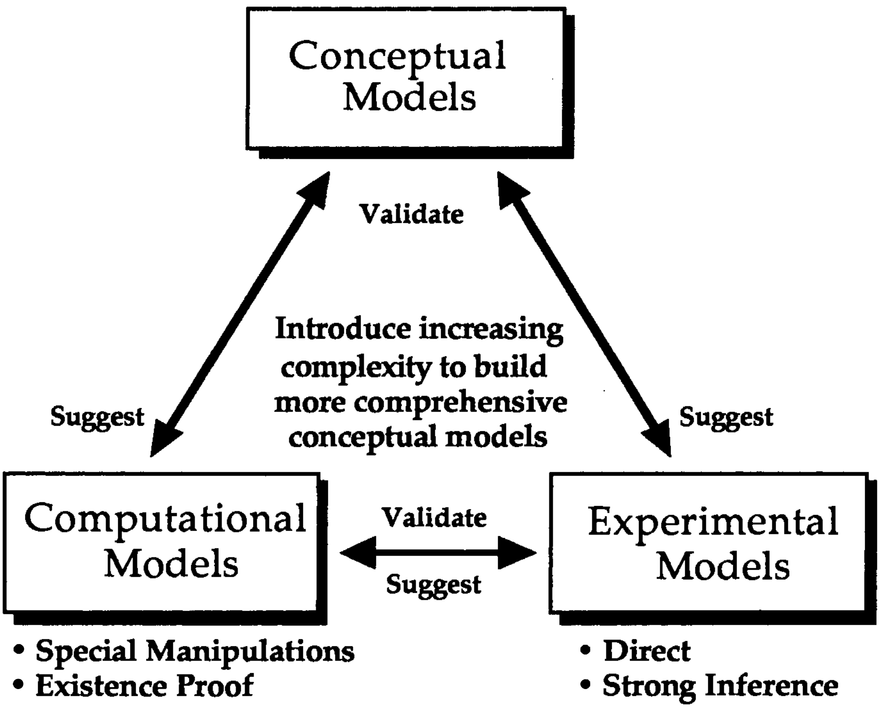

Figure 1.3 Triangle strategy. Comprehensive conceptual models can be validated by the tools of computational modellers and experimenters. Experiments and computational models can suggest new conceptual models.

Today, with advances in computing, computational models can be designed to implement a conceptual model. These implementations can be structured as networks of processing elements simulating the brain, as control processes simulating a system, as expert systems manipulating knowledge, or even as robot systems simulating human movement. A computational model, while not the actual system, can act as an existence proof of a conceptual model. An advantage of simulation techniques is that they can include perturbations and manipulations that are impossible or unethical to do with humans. The power of computational models lies in the ability to simulate a system, exploring different processing architectures and manipulating various parameters. These models can provide clear-cut predictions for experimental evaluation at both the behavioral and neural levels. At the very least, computational models provide direction for further thinking.

Computational models suggest critical experiments for understanding human behavior. In turn, experiments can provide data to assess the validity of computational models of human behavior. Thus, conceptual models can be validated and extended using both computational and experimental approaches. The power of these tools is that levels of complexity can be introduced into experimental and computational models in order to develop a more comprehensive conceptual model.

Our purpose in writing this book together is to promote an integrated view and common vocabulary that will lead to advances in understanding complex systems. Using the triangle strategy from Figure 1.3, we present computational models and empirical studies in a comprehensive study of prehension. Understanding human prehension is an enormous problem. In behavioral studies, measures may be made as to where the hand is placed in space and how the joints of the arm work. At the kinematic[2] level, it would be the velocity and acceleration of various features of the arm; in terms of dynamics[3], the forces acting on the arm would be measured. But the hand, with its small bones and approximately 28 degrees of freedom[4], presents an enigma:

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[2]Kinematics is the study of the position, velocity, and acceleration of bodies through space without regard to the forces that might be causing that movement.

[3]Dynamics is the study of the net forces and torques acting on a body over time. This is distinguished from statics, which is the study of the net forces and torques acting on a body at rest. Kinetics encompasses forces as well, because it is the dynamics in biomechanical systems.

[4]Degrees of freedom refer to the independent states of a system or the number of values free to vary independently.

how can hand movements be quantified so that we can explore how the CNS might be controlling it? Should the movement of each individual joint be studied? But then, what happens in an injured hand when fingers are lost? Does the CNS change? Is the brain of the person born with fewer than five fingers fundamentally different from the person with a more usual hand?

This book provides a framework and comprehensive study of the functionality of human prehension. From our earlier discussion about hand and tool use, several key points are identified that will be the focus for this text. Analyzing how the hand interacts with various objects, we see that the hand adopts a wide variety of task-specific postures for applying forces. In the next chapter, we summarize ways that researchers in a variety of fields have looked at prehensile behaviors. These include classifications from anthropology, hand surgery, hand rehabilitation, robotics, and developmental psychology. This is a useful starting ground for analyzing prehension. More important, however, is to find a way to go beyond classification toward quantification in order to seek out the variables that the CNS is controlling in prehension.

Part II of the book has to do with serial order. When reaching to grasp an object, the hand and arm move in an unrestrained fashion to get the hand to the object. Then contact is made with the object. This involves a sequence in which first an unrestrained movement occurs, then a guarded one, and finally a compliant movement occurs as the hand grasps the object. These steps are identified as distinct phases during prehension. In Chapters 3-7, prehension is analyzed as it unfolds in time. Each phase is examined individually to identify what makes it distinct from previous phases. Here existing evidence for movement characteristics and the sensorimotor integration that uniquely defines each phase is considered in detail. This analysis comes from the behavioral, biomechanical, neural, and robotics literature. Experimental results are used to examine object properties and task requirements, addressing issues such as the effect of context and intention, and the transitions between the phases. Chapter 7 summarizes the evidence from experiments and ideas from computational models into a new conceptual model of the phases of prehension. We identify hypotheses for empirical and computational studies to help validate and extend the model. From a research perspective, computational modelling and empirical studies are closely intertwined and can be used to validate and further develop the conceptual models.

Part III of the book looks at the constraints over the serial order. A major challenge in developing a comprehensive model is that prehensile behavior emerges from computations in a multidimensional constraint space. Chapter 8 reviews prehension, focusing specifically on these constraints. Classes of constraints which must be included in a complete model of human grasping are identified, and the levels in the system at which the constraints are operating are discussed. These constraints include social, motivational, functional, physical, neural, anatomical, physiological, evolutionary, and developmental ones. Some constraints are time varying, others are not. Details of the constraints are discussed, thus helping to define their role in the modelling process. Chapter 9 reviews the problem being solved by the CNS. Using the black box metaphor, a review is made as to the nature of the object, the task, the hand, and the controller of prehensile behavior. Potential applications for the work compiled in this volume are discussed.

For those readers wishing an introduction or review of topics, we include Appendices. For functional anatomy of the upper limb of humans, Appendix A is provided. It includes a description of the skeletal and joint structures from the shoulder girdle to the fingers and a review of the degrees of freedom permitted by these joints (e.g., a hinge joint like the elbow has one degree of freedom, a ball and socket joint like the shoulder has three degrees of freedom). In addition, there is a review of the single and multi-joint muscles in the upper limb, showing their primary actions, the number of joints they cross, and their peripheral and segmental innervation. Sensations and spinal innervation of the upper limb are also included. Appendix B includes summary tables detailing prehensile classification systems, for both adult and developmental postures. Appendix C provides a straightforward tutorial on the computational modelling concepts presented in this book. It contains definitions of terminology and simple examples for readers wishing to gain an understanding of the computations. Finally, Appendix D provides information on a topic closely related to the human hand: multi-fingered robot and prosthetic hands. Throughout history, engineers have tried to capture the complexity of the human hand into some mechanical device. Today, with recent advances in space-age materials and electronics, sophisticated multi-fingered mechanical hands have been built for use by amputees and on robot manipulators. This appendix describes some of the systems being used in the field and at research institutions.

In summary, our overall approach can be stated as follows. After examining classifications of prehension, we identify unique phases in prehension. For example, a grasp strategy suitable for the task is chosen before movement occurs. During movement, the hand is configured for placement on the object, and once contact is made, a stable grasp is established and maintained. However, studying the phases isn't sufficient. Many constraints are acting at different levels and on the different phases of prehensile activity. For example, the way the hand is shaped in order to comply with object properties is partially a function of anatomical and biomechanical constraints, while the chosen set of object properties that must be complied with is more a function of the task constraints. We make explicit these constraints, examine experimental evidence and suggest how computational models can be developed for capturing hand function. By critically evaluating the current knowledge about the hand, our goal is to make explicit a common language for understanding human prehension across robotics, cognitive science, kinesiology, computer science, psychology, neuroscience, medicine, and rehabilitation.

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Chapter 2. Prehension

"Although in most prehensile activities either precision or power is the dominant characteristic, the two concepts are not mutually exclusive."

-- J. R. Napier (1956, p. 906)

2.1 Overview of Prehension

Prehension involves the taking hold of an object for a purpose such as manipulating it, transporting it, or feeling it. One might also grasp for the purpose of transporting or rotating one's whole body about the object, as in climbing or gymnastics. On the kinetic level, prehension entails applying forces during interaction with an object. Stable grasping adds the requirement that forces are applied by hand surfaces in opposition to other hand surfaces or external objects in order to overcome slight perturbations. On the kinematic level, prehension involves the orienting and posturing of the hand and fingers, with the appropriate transportation of the limb to the correct location in space. In this book, prehension is defined as *the application of functionally effective forces by the hand to an object for a task, given numerous constraints*. This definition places an emphasis on the task and functional aspects of the problem. The words 'functionally effective' are used to highlight the fact that the forces must be applied within the functional constraints of the task; i.e., while forces can be used to effect a stable grasp and impart motions as needed in a task, there are functionally specific demands on how this is accomplished, such as the precision requirements or stability needs. As well, considerations address how the hand is postured to apply these forces, and how the dynamic postures used for applying these forces are set up as the hand reaches out toward the object.

The human hand has a variety of ways to grasp objects stably. But there are constraints on the ways that the hand can be postured, as well as on the potential success of a chosen posture. These include both functional constraints and physical constraints[1]. Functional constraints are not so much a property of the object to be grasped, but more a property of how the object will be used within the task. The task goals and subgoals determine functional constraints. Schmidt

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[1]Constraints are examined in more detail in Chapter 8.

(1988) referred to the task goal as the 'environmentally defined goal', distinguishing it from the muscular activity needed to produce the desired environmental outcome. A fundamental functional constraint is that the object not be dropped. This means that one key goal in most prehensile tasks is the establishment and maintenance of a stable grasp. The posture used by the hand during the task must be able to overcome potential perturbations or take advantage of the anticipated forces acting on the object. These include gravity and, depending on the actual task, there are likely additional inertial and/or coupling forces. Another functional constraint in some tasks is the ability to manipulate the object. In order to accomplish the goal of the task, the object is transported or motion is imparted to the object, with potential instabilities occurring along the way. The shaping of the hand prior to contact reflects these anticipated task requirements.

Underlying these functional constraints are physical constraints, including: properties of the objects; forces like gravity and friction; and properties of the arm and hand. For the object, these include such properties as surface compliance, shape, texture, temperature, size, etc. (see Chapter 4 for those object properties assessed by vision; and Chapter 6 for those assessed by touch). Object size and shape can delimit the number of fingers potentially contacting a surface; the availability of object surfaces will constrain the orientation and potential contact locations of the hand. With respect to forces, gravity is a constant. In contrast, friction arises from the interaction between the hand and the object. Physical constraints also include properties of the arm and hand. Postures are created by the muscles of the hand directing the bones into some configuration, based on the motion capabilities of the various joints[2]. Each joint provides one or more motion capability (each capability for motion is called a degree of freedom, df). Degrees of freedom refer to the independent states of a system or the number of values free to vary independently. In the upper limb there are close to 40 df, of which about 30 df are in the hand and wrist. The degrees of freedom problem in motor control refers to the problem of coordination and control by the central nervous system, and has been phrased

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[2]For those readers wishing an introduction or review of upper limb functional anatomy of humans, see Appendix A. It includes a review of the degrees of freedom permitted by the joint structures of the upper limb (e.g., a hinge joint like the elbow has one degree of freedom, a ball and socket joint like the glenohumeral joint of the shoulder has three degrees of freedom). As well, there is a review of the pattern of single and multijoint muscles in the upper limb, and the peripheral and segmental innervation of these muscles by the nervous system.

by Kugler et al. (1982) as follows, "How can the very many degrees of freedom of the body be regulated in the course of activity by a minimally intelligent executive intervening minimally?" In separating the environmentally-defined goal from this motor problem, Schmidt (1988) pointed out that while it is pretty well clear what the overall goal is, it is not clear how to coordinate muscular activity to achieve it. He suggested that a motor goal can be viewed as a spatial-temporal pattern of action that, when produced accurately, will achieve the environmentally defined goal. But, of course, he pointed out that different patterns of action will result in the same overall goal.

The definition of prehension stressed that 'functionally effective forces' need be applied. In general, the functional demands on a posture can be summarized as follows:

a) apply forces to match the anticipated forces in the task (stable grasp)
b) impart motion to the object (manipulate) or transport the object as necessary
c) gather sensory information about the state of the interaction with the object during the task in order to ensure grasping and manipulative stability

For the hand, different postures present different degrees of available force, of available motion, and of available sensory information. For a task, there are a variety of possible postures that could be used. As a starting point for understanding how the task requirements can be matched by the functional capabilities of the hand, an examination of significant taxonomies of hand postures is now made.

2.2 Prehensile Classifications

The question of how the human hand works has been addressed by engineers who want to duplicate it in mechanical devices, and by medical scientists and therapists who want to help patients in functional hand usage. For example, a simple taxonomy was developed by G. Schlesinger in Germany in 1919 as a way to categorize prehensile functionality for prosthetic hands due to injuries from World War I, as seen in Figure 2.1. Schlesinger's classification represents one of many attempts that have been made to classify hand postures by researchers from different perspectives for medical, clinical, occupational, and industrial applications. These taxonomies are summarized in Table 2.1[3]. Some classifications are more anatomical, but most focus on functionality, particularly for evaluating remaining capabilities after accidents, disease or surgery. Each taxonomy offers new insights into the complexity of human prehension. Yet, across this diverse set, themes are repeated, suggesting the possibility of a unifying view, as will be seen in this chapter. Selective classifications are considered in order to develop the important roles of hand, object, and task characteristics in the selection of an appropriate, efficient grasp posture. While this book does not address developmental aspects of human prehension in detail, taxonomies for looking at the development of prehension in infants are also summarized in Appendix B[4].

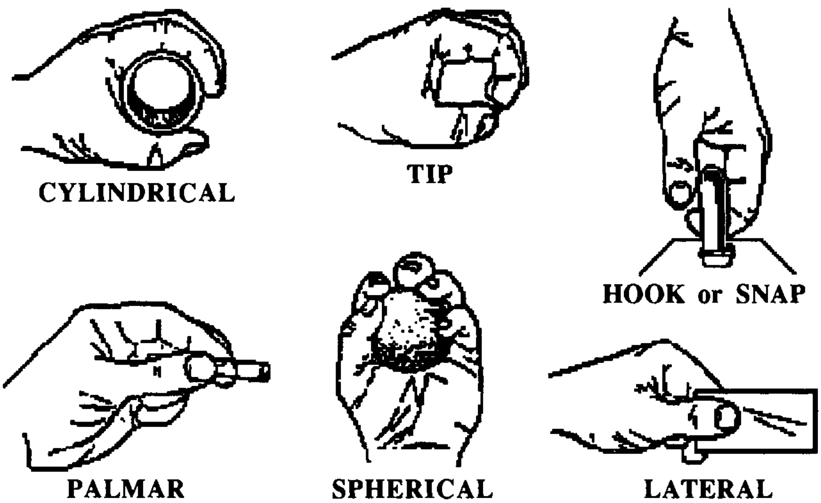

Figure 2.1 Schlesinger's classification of prehensile postures. This set was a minimum set of a more comprehensive one he developed. See text for details (from Taylor and Schwartz, 1955; adapted by permission).

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[3]A complete analysis of prehensile classifications is provided in Appendix B.

[4]We allude to some of the developmental issues throughout the book. We refer the interested reader to excellent papers and reviews (Bower, 1974; Forssberg et al., 1991, 1992; Halverson, 1931; von Hofsten, 1990; Piaget, 1953; Twitchell, 1970).

Table 2.1 Prehensile classifications developed in anthropology, medicine, biomechanics, robotics, and occupational therapy. (continued...)

Researchers	Posture names	
Cooney and Chao (1977)	grasp palmar pinch	tip pinch lateral pinch
Cutkosky (1989)	large diameter heavy wrap small diameter heavy wrap medium wrap adducted thumb wrap light tool wrap disk power grasp spherical power grasp 5 finger precision grasp	4 finger precision grasp 3 finger precision grasp 2 finger precision grasp disk precision grasp spherical precision grasp tripod precision grasp lateral pinch hook, platform, push
Elliott and Connolly (1984)	palmar grip dynamic tripod pinch squeeze twiddle rotary step linear step	rock radial roll index roll full roll interdigital step palmar slide
Griffiths (1943)	cylinder grip	ball grip
Iberall et al. (1986)	palm opposition pad opposition	side opposition
Jacobson and Sperling (1976)	coding system for fingers, finger positions, finger joint positions, contact surfaces, and orientation of object's longitudinal axis with respect to the hand	
Kamakura et al. (1980)	power grip-standard power grip-index extension power grip-distal power grip-extension parallel mild flexion grip tip prehension surrounding mild flexion grip	parallel extension grip tripod grip tripod grip-var. 1 tripod grip-var. 2 lateral grip power grip-hook adduction grip
Kapandji (1982)	cylindrical palmar spherical palmar digito-palmar subterminal pollici-digital terminal pollici-digital subtermino-lateral pollici-digital interdigital latero-lateral tridigital grips	tetradigital-pulp & side tetradigital pulp to side tetradigital by pulp pentadigital-pulp & side panoramic pentadigital pentadigital cleft directional grip gravity-dependent grips dynamic grips

Table 2.1 Prehensile classifications (continued).

Researchers	Posture names	
Kroemer (1986)	disk grip collect enclosure power grasp pinch or pliers grip tip grip	lateral grip precision or writing grip hook grip finger touch palm touch
Landsmeer (1942)	power grasp	precision handling
Lister (1977)	span power grasp precision pinch pulp pinch	chuck grip key pinch hook grip flat hand
Liu and Bekey (1986)	power grasp cylindrical grip span precision pinch	pulp pinch chuck grip lateral pinch hook grip
Lyons (1985)	encompass grasp precision grasp	lateral grasp
McBride (1942)	whole hand grasping palm, digits grasping	thumb, finger grasping
Napier (1956)	power grip precision grip	combined grip hook grip
Patkin (1981)	power grip external precision grip internal precision grip	pinch grip double grip (ulnar storage)
Schlesinger (1919)	open fisted cylindrical grasp close fisted cylindrical grasp spherical prehension palmar prehension (pincer) tip prehension lateral prehension hook prehension	cylindrical w/ add. thumb flat/thin (2 finger) pincer large (5 fingered) pincer three-jaw chuck nippers prehension
Skerik et al. (1971)	power grip two point palmar pinch three point palmar pinch	tip pinch link grip (lateral pinch) hook grip
Slocum and Pratt (1946)	grasp pinch	hook
Sollerman (1980)	diagonal volar grip transverse volar grip spherical volar grip pulp pinch	tripod pinch five-fingered pinch lateral pinch extension grip
Taylor (1948)	palmar prehension (3 jaw chuck) tip prehension	lateral prehension

2.2.1 Hands as tools

Schlesinger (1919) put forth a now classic taxonomy that was developed to capture the versatility of human hands for designing functionally-effective prosthetic hands (see Figure 2.1). He used tools and fasteners to describe the special purpose nature of various postures. For example, simple, regularly shaped objects, symmetrical about an axis internal to the object, could be held by a pincer or palmar grip, acting much as a set of pliers or as a set of nippers for smaller objects. A hook grip could be used for suitcase handles and a ring or cylindrical grip could be used for holding a hammer.

Seeing the limitations of sensor-based prosthetic design in his time, Schlesinger focused on determining what specific functionality was needed for grasping and holding various objects (e.g., book page, matchbox, pen, etc.). From this analysis[5], Schlesinger devised a minimum set of six grasp postures (see Figure 2.1):

a) An open fist grip for tools, such as for a hollow cylinder and beer mug. This is the ring function Schlesinger described, and the posture has been called <u>cylindrical prehension</u> (see, for example, Taylor and Schwartz, 1955). It can also be a closed fist grip for thin objects, such as a shaft.
b) A posture for spherical objects, such as a ball. The fingers can spread, while the palm can be arched. This is the most adaptable posture and is called <u>spherical prehension</u>.
c) A posture for flat, thick objects. Movement is provided by fingers for grasping objects such as a large box and a matchbox. This is the pliers function; this posture has been called <u>palmar prehension</u>.
d) A posture for sharp, small objects, such as a needle, pen, small bearing, and book page. Again, movement is provided by the fingers. This is the nippers function and the posture is called <u>tip prehension</u>.
e) A posture for thin, flat objects, such as a piece of paper. In this case, movement is provided by the thumb. This posture is called <u>lateral prehension</u>.
f) A posture for heavy loads, such as suitcases. This is the hook function, and the posture is called <u>hook prehension</u>.

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[5] Schlesinger sometimes arbitrarily discarded functionality because it was 'uneconomical', as in grasping a file!

Schlesinger's classification incorporated three critical notions: object shape (cylindrical, spherical), of particular hand surfaces (tip, palmar, lateral), and hand shape (hook, close fist, open fist). Importantly, he noted how the hand, with its ability to spread the fingers and arch the palm, can grasp arbitrary objects. In the 1919 book, Schlesinger did not specifically name any of the grasps, other than the 'fist'; instead, he used object characteristics and tools as methods to describe the postures. The English terminology used by Taylor and Schwartz doesn't capture each posture's functionality as explicitly as did Schlesinger. In addition, what has been translated into English has been only the minimum set of postures that was developed for unilateral amputees. His complete characterization of human prehension, as listed in the third column of Table 2.1, included five other postures, such as the closed fisted cylindrical grasp with the thumb adducted and the three-jaw chuck, discussed later in this chapter.

An alternative approach was developed at the end of World War II in order to evaluate the functional loss of hand use due to injuries. As surgeons in the Army Medical Corps, Slocum and Pratt (1946) identified three prehensile postures: the grasp, pinch, and hook. The grasp was the 'combined action of the fingers against the opposed thumb and palm of the hand,' the pinch was 'apposition of the pad of the thumb against the pads of the opposing fingers,' and the hook was a posture where 'the fingers are flexed so that their pads lie parallel and slightly away from the palm' (Slocum and Pratt, 1946, p. 491). Simple and elegant, this approach collapses Schlesinger's many postures into three functional features of the hand. Using Schlesinger's terminology, these can be characterized as the ability to act like a ring, to act like a pliers/nippers, and to act like a hook.

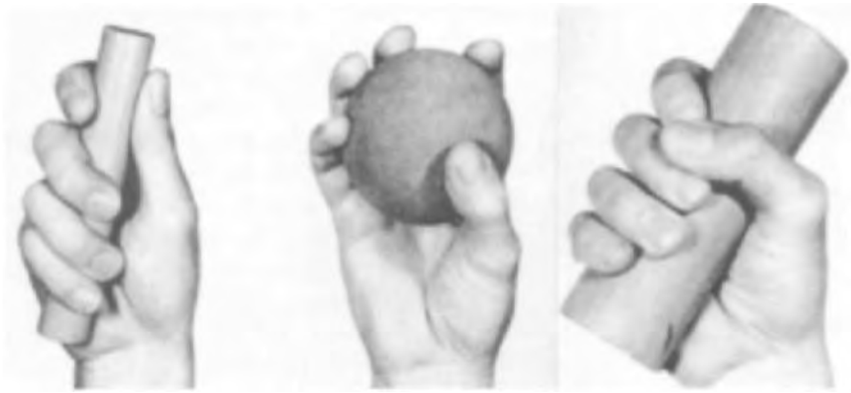
2.2.2 Power vs. precision requirements

While Schlesinger's analysis is extensive and Slocum and Pratt's insightful, the major problem with them is that they don't address the requirements of the task. For example, people use different hand postures when picking up a pen to write with it, compared to picking it up to place it in a container. For a classification that deals with *task features*, Napier's work is more useful.

John Napier published a classic paper in 1956 addressing the question 'what is a scientific terminology for describing the movements and functions of the hand as a whole?' Napier argued that Slocum and Pratt's postures (grasp, pinch, hook) were not clearly defined nor comprehensive, and that a classification was needed that was based on both a functional and anatomical description of the human hand in prehension. Major points that Napier made include the following:

1. Influences on the posture chosen for the grasp come from multiple sources. These include object shape, size, weight, surface characteristics (texture, temperature, and dryness), and human motivations (fear, hunger, distaste, etc.). He stressed, however, that the most important influence on the chosen posture is *the goal of the task*; i.e., the intended activity.
2. He described prehension as the 'application of a system of forces in a given direction' (Napier, 1956, p. 906), and argued that prehensile tasks can be resolved into power and precision requirements (with one fundamental requirement being a secure grasp). Power requirements relate to the ability to apply forces and resist arbitrary forces that may be applied to the object; precision requirements involve small adjustments of posture in order to control the direction in which force is being applied.
3. Napier's insight was to suggest that the power and precision requirements of tasks could be met by the power and precision capabilities of the human hand. The power requirements of a task could be met by the hand's ability to oppose arbitrary forces, especially when the thumb is used to reinforce the action of the fingers. Meeting the precision requirements of a task could be accomplished by placing the skin receptors in contact with the object, providing the nervous system with cutaneous information for making the fine adjustments.

Napier's classification is presented in Figure 2.2. Anatomically, Napier defined the power grip as follows (see Figure 2.2a and refer to Appendix A for assistance with anatomical terminology). The thumb is in the plane of the palm; its metacarpophalangeal and carpometacarpal joints are adducted. The fingers are flexed, laterally rotated, and inclined towards the ulnar side of the hand. The fingers flex in opposition to the palm, with the degree of flexion depending on object dimensions. The wrist is positioned with ulnar deviation, neutral between extension and flexion. An element of precision in the power grip depends on thumb placement, ranging from some precision when it is adducted and able to contact the object and gather sensory information (Figure 2.2a) to no precision (and maximum power) when the thumb is abducted as in the 'coal hammer' grip (Figure 2.2c).



A. POWER GRASP B. PRECISION GRASP C. COAL HAMMER

Figure 2.2 Napier's classification of prehensile postures. He focused on the goal of the task, i.e., whether precision or power was required, and argued that the hand could form into either a: A. power grasp or B. precision grasp to match these task requirements. C. A type of power grasp, called a coal hammer grip, occurs when the thumb is abducted and brought onto the dorsal surface of the fingers (from Napier, 1956; reprinted by permission).

The precision grip (see Figure 2.2b), according to Napier, occurs when the thumb is abducted and medially rotated at the metacarpophalangeal and the carpometacarpal joints. The fingers are flexed and abducted at the metacarpophalangeal joints, producing a degree of axial rotation in the digits. The wrist is dorsiflexed (extended), positioned between ulnar and radial deviation. The object is pinched between the flexor aspects of the fingers and the opposing thumb, specifically between the thumb and index finger, which are best adapted to performing fine control and thus more useful with smaller objects.

Napier's insights stemmed from his research into the evolution of the hand. In comparing the human hand to the hand of other primates, he was able to recognize its simplicity and general purpose nature. Arguing that the human hand is highly unspecialized, he pointed to the dead ends that extreme specialization can lead to, such as the potto (stubbed index; specialized for firm gripping), the gibbon (long fingers, short thumb; specialized for brachiation), and the aye-aye (extremely skinny middle finger; specialized for scooping insects from holes). Extreme specialization for one purpose limits other possible uses of the hand. Ultimately, he was able to sense that even though tasks are complicated and full of variety, there are two fundamental qualities to tasks--their precision and power requirements--and he was able to recognize that the human hand could match these.

In the robotics literature, Cutkosky and colleagues (Cutkosky, 1989; Cutkosky and Howe, 1990; Cutkosky and Wright, 1986b) extended the Napier precision/power dichotomy by further classifying power grasping into nine subordinate types and precision grasping into seven subordinate types using a set of grasp attributes (see Figure 2.3). In power grasps, the emphasis is on stability, a grasp attribute defined as the ability to resist external forces without slipping and return to nominal position, and security, or the ability to resist slipping. In precision grasps, the emphasis is on dexterity, which is defined as how accurately fingers can impart larger motions or forces, and sensitivity, or how accurately fingers can sense small changes in force and position. In addition to grasp attributes, Cutkosky and Howe use object characteristics to refine postures in a style similar to, but more precise than, Schlesinger. Prismatic grasps are wrap postures (i.e., cylindrical grasps) that enclose a tool with a long symmetry. A circular posture, on the other hand, is used for objects with radial symmetry (i.e., spherical grasp).

2.2.3 Precision handling and dynamic grasps

Identifying postures is useful for describing a static view of a hand posture. However, many grips[6] are associated with actions. Landsmeer (1962) extended Napier's dichotomy, rethinking the precision grip as precision handling, thus highlighting the dynamic aspect of the movements during fine translations, rotations and complex manipulations. Power grips immobilize the object so that there is a definite static phase once the object has been grasped, whereas precision handling does not have a definite static phase. Rather, Landsmeer suggested that grasping the object in opposition between the thumb and finger pads enables greater variety of movements, because the fingers can impart those movements. Kapandji (1982, p. 272) called these dynamic grips since 'the hand can act **while** grasping', and gave numerous examples, such as top turning, lighting cigarettes, pushing

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[6]We note that others have made a distinction between the words 'grip' and 'grasp'; for example, Malek (1981) suggested a grip is a static posture and a grasp is the dynamic unfolding of a posture. Here, for simplicity, the two words are used interchangeably.

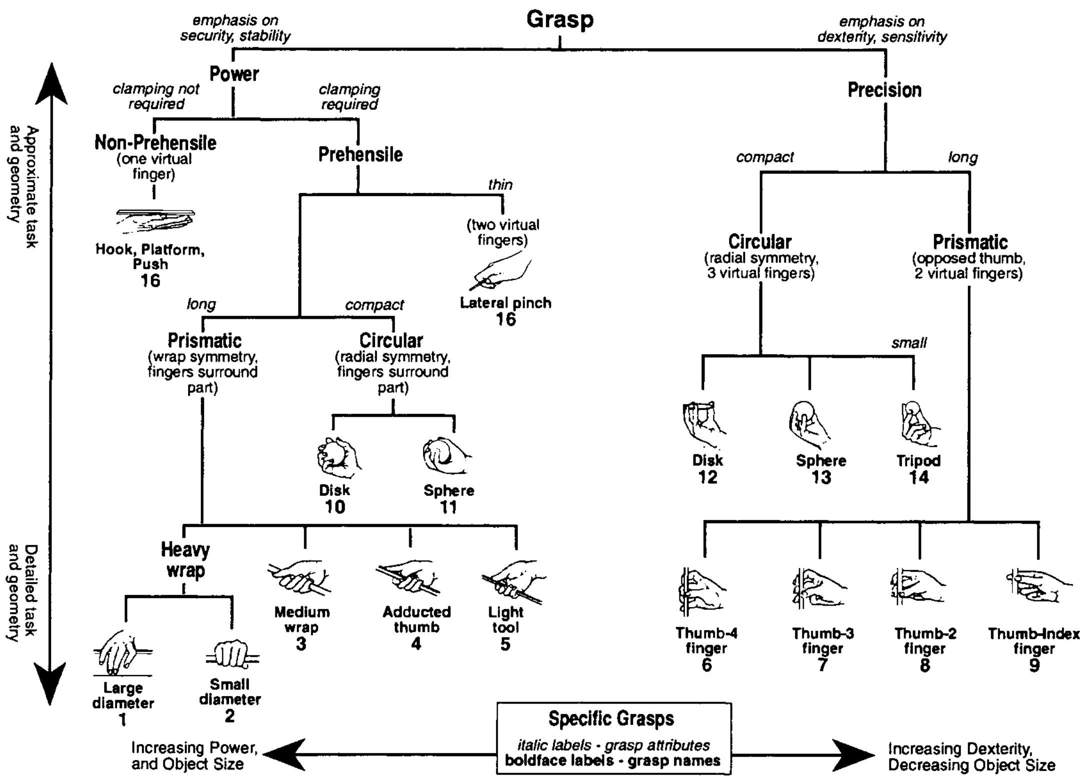

Figure 2.3 Cutkosky and Howe's classification. On the left are power grasps, and on the right, precision grasps. A posture is parameterized by task attributes (forces and motions) and object geometry (from Cutkosky and Howe, 1990; reprinted by permission).

the button on a spray can, and cutting with scissors. Landsmeer provided an extensive anatomical analysis of precision handling and suggested that a key characteristic of it was the fact that the metacarpophalangeal joints are in extension while the interphalangeal joints are in flexion.

An important aspect of the human hand is the interplay between the thumb, index finger, and middle finger. Due to the thumb's placement on the hand, its six degrees of freedom, and its ability to oppose the other fingers, a posture called a tripod or three jaw chuck can be formed. This is a powerful gripping mechanism used in tools such as drills for holding drill bits. Included in Schlesinger's full classification and other classifications as noted in the table, the tripod can be used to grasp a piece of chalk between the thumb, index, and middle fingers. Additionally, a variation of this can be formed using a fourth contact point. This dynamic posture, used in writing with a pen or pencil, has been called the external precision grip or writing grip (Patkin, 1981), dynamic tripod (Wynn-Parry, 1973), and tripod grip--variation 1 (Kamakura et al., 1980). As seen in Figure 2.4b, the object is held by the pads of the thumb, index, and middle fingers, with an extra contact made by the thumb cleft or side of the index base. The relative lengths of these digits and the complex interactions of their degrees of freedom give rise to the thumb's ability to oppose the fingers and thus impart fine motions to the object. Using the cleft of the thumb as an extra contact point counteracts torques being applied to the object, as with the pen or pencil being applied to a piece of paper in writing.

In terms of dynamic grasps, Elliott and Connolly (1984) noted that care has to be taken in distinguishing anatomical features from functional features of the hand. They argued that Landsmeer's extension to Napier's classification did not clarify this difference, and therefore, in their taxonomy, they distinguished two functions: palmar grips (for immobilizing the object) and digital manipulative patterns (of independently coordinated digit movements). Anatomically, palmar grips are usually power grips, but digital manipulative patterns include more than precision handling as it was anatomically defined by Landsmeer. Elliott and Connolly identified three basic classes of manipulative movements: simple synergies, reciprocal synergies, and sequential patterns. Simple synergies are where 'all movements of the participating digits are convergent flexor synergies' and include pinch (between thumb and index pads), dynamic tripod (holding a pen), and squeeze (squeezing rubber bulb or syringe). Reciprocal synergies include twiddle (roll small object to and fro between thumb and index), rock (screwing on a freely moving lid), radial roll (winding a watch), index roll, and full roll. Sequential patterns include rotary step, interdigital step (turning a pen end over end), and linear step. The palmar slide is an example of an action that requires both digital movement and power, as in separating a pen cap from a pen with one hand. Elliott and Connolly's digital manipulative patterns are revisited in discussing manipulation in Chapter 6.

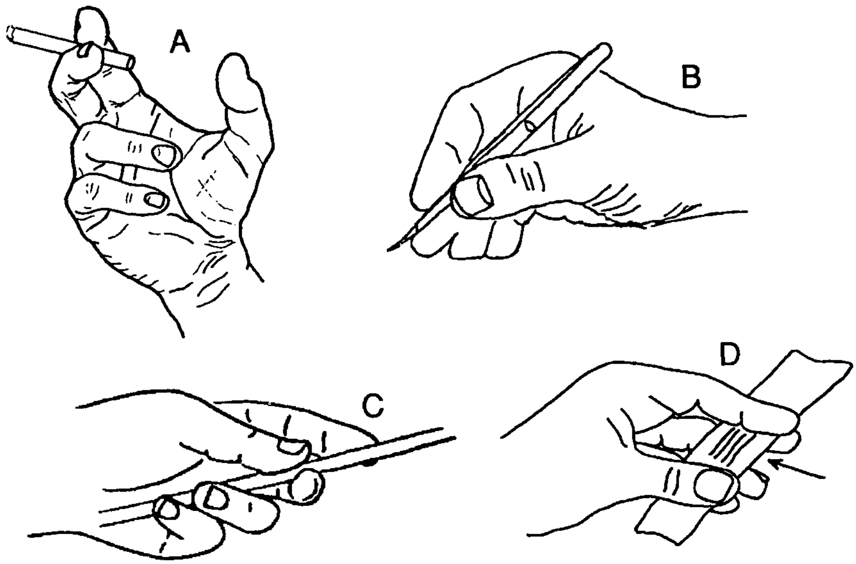

Figure 2.4. Various postures. A. The adduction grip. B. External precision grip. C. Internal precision grip. D. Double grip. (A from Kapandji, 1982; B,C from Patkin, 1981; D from Patkin & Stanley, 1981; reprinted by permission).

2.2.4 The bridge between power and precision: the lateral pinch

Hand surgeons and occupational therapists at the University of Iowa developed their own taxonomy with the goal of facilitating uniform observations (Skerik, Weiss, and Flatt, 1971). They pointed out that the use of symbolic terms, such as cylindrical and spherical grips, is unfortunate since it 'promotes observation and concern with the shape of the test object rather than concentration on the hand using the test object' (Skerik et al, 1971, p. 102). Unique to their taxonomy is the argument that the lateral pinch (see Figure 2.1) is a link grip or a bridge between power grips and precision handling since 'it possesses some of the characteristics of both precision and nonmanipulative grasps but cannot be considered a pure form of either' (Skerik et al, 1971, p. 101). Occurring between the thumb and radial side of another finger, the lateral pinch is similar to a power grasp in that it is an isometric muscular contraction. At the same time, manipulation can occur using movements of the thumb and/or finger, using the thumb pad in particular to provide sensory information about the object's state. Lacking is both the strength of the power grasp and the manipulative range of precision handling. It is interesting to note that whereas most other researchers put the lateral pinch as a precision operation, Cutkosky and Howe placed it on the power grasp side.

2.2.5 The adduction grasp

An interesting feature of the human hand is that there are a multitude of surfaces, oriented in different ways. Objects, such as cigarettes, can even be held between the fingers. In a formal classification study performed by Kamakura et al. (1980), seven subjects were photographed holding 98 different objects and a hierarchical classification was developed. Fourteen postures were observed within four major types: power, precision, intermediate, and adduction. Postures were classified into types based on finger and/or palm involvement and amount of contact area on the hand. Of note here, a posture called the adduction grip (see Figure 2.4a) was used for holding a small, light object such as a cigarette between the index and middle fingers. Other uses of this posture are seen when small objects need to be removed from tight places, such as grasping coins from pockets. Napier (1980) calls this the scissor grip. In contrast, Kapandji (1982) describes this grip anatomically as the interdigital latero-lateral grip.

2.2.6 Gravity dependent grasps

According to Napier (1956), the hook grip (illustrated in Figure 2.1) doesn't involve the thumb and is used when precision requirements are minimal and power needs to be exerted for long periods, as in carrying a suitcase. In the 1970's, the French hand surgeon Kapandji developed an extensive taxonomy in an attempt to identify hand functionality for reconstructive surgery (Kapandji, 1982). He suggested that the hook grip, or the claw, is a gravity dependent grasp. Very interestingly, he identified other ways the hand can use gravity, including: cupping the hands into the shape of a spoon; and flattening out the hand as a platform, as a server does in holding a tray. The gravity dependent postures do not involve two hand surfaces opposing each other. Instead, a hand surface is opposing a task-related force or torque.

2.2.7 The finger as antenna

Various researchers have noted postures where the index finger is used effectively much as an antenna listening in on the state of the object or in on the interaction of the tool with the environment. For example, when a surgeon holds a scalpel, the index finger is placed along the edge while the object in turn is grasped by the other fingers within the palm (see Figure 2.4c). This posture has been called the internal precision grip (Patkin, 1981) and the directional or centralized grip (Kapandji, 1982). It has been observed in the grasping of a screwdriver, a conductor's baton, and a knife. Kamakura et al. (1980) suggested it was a variation of the power grip and called it a power grip--index extension. Another example offered by Patkin is the way surgeons use the index finger for sensing tissue thickness, while using their ulnar fingers and thumb to manipulate the forceps.

However, just as an antenna both receives and transmits, so can the index finger. Besides sensing information about the forces acting on the object, the index finger can impart fine motions to it. It can also counteract larger forces, as in stabbing a piece of meat with a fork or cutting it with a knife. This notion of finger-as-antenna can be generalized to any finger or fingers. The thumb, in effect, could be performing this very function in Napier's power grasp (depicted in Figure 2.2a).

2.3 An Opposition Space Classification

2.3.1 Types of oppositions

Another way to analyze what the hand is doing in prehension is to focus on the fact that a posture involves at least two forces[7] being

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[7]This statement can be qualified in two ways. First, two forces don't make a grasp necessarily stable, as is discussed in Chapter 6. Secondly, one force can be used to balance an object, opposing gravity directly. This palming or balancing is not

applied in opposition to each other against the object's surfaces. Iberall, Bingham, and Arbib (1986) used the term opposition[8] to describe three basic directions (or primitives) along which the human hand can apply forces. A prehensile posture then consists of combinations of these primitives. They are as follows (see Figure 2.5):

1) PAD OPPOSITION: occurs between hand surfaces along a direction generally parallel to the palm. This usually occurs between volar surfaces of the fingers and thumb, near or on the pads. An example is holding a needle or small ball.
2) PALM OPPOSITION: occurs between hand surfaces along a direction generally perpendicular to the palm. Grasping a large hammer or screwdriver are examples of palm opposition.
3) SIDE OPPOSITION: occurs between hand surfaces along a direction generally transverse to the palm. As an example, one holds a key between the volar surface of the thumb and the radial sides of the fingers. Of course, it can occur between the sides of the fingers, as in holding a cigarette.

2.3.2 Virtual fingers

In observing how subjects grasped different sized mugs (Figure 2.6), Arbib, Iberall, and Lyons (1985) noted that different numbers of fingers were used depending on the length of the mug handle. Yet, the task remained basically the same: a finger was placed on top of the handle, one or more fingers were placed inside the handle, and if available, fingers were placed against the outside of the handle. They suggested that each of these functions were being performed by a virtual finger (VF) as the method of applying the force. A virtual finger is an abstract representation, a functional unit, for a collection of individual fingers and hand surfaces applying an oppositional force. Real fingers group together into a virtual finger to apply a force or torque opposing other VFs or task torques. Figure 2.6 shows how the number of real fingers used can be a function of an object property, such as handle size. For a teacup with a very small handle (Figure 2.6a),only one finger fits inside the handle, providing an upward force from within the handle. Here, the thumb, as virtual finger 1

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stable either.

[8]Opposition used here should not be confused with the term 'thumb opposition', which describes a complex movement of the thumb's six degrees of freedom as it rotates into opposition to the finger pads (see Appendix A).

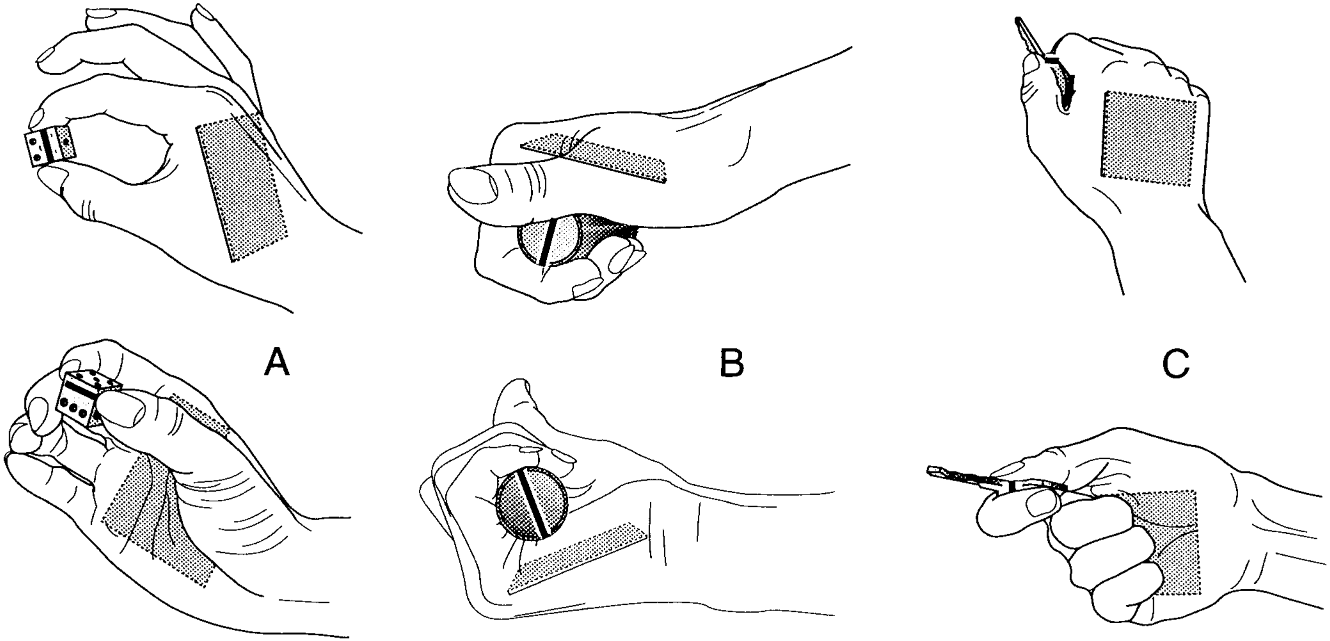

Figure 2.5 Prehensile postures consist of combinations of three basic ways that the hand can provide oppositions around objects. The solid line shows the opposition vector seen in the object. The shaded area represents the plane of the palm. Note the orientation of the opposition vector relative to the plane of the palm. A. Pad opposition occurs along an axis generally parallel to the palm, B. Palm opposition occurs along an axis generally perpendicular to the palm, and C. Side opposition occurs along an axis generally transverse to the palm.

Figure 2.6 Grasping different sized mugs. The hand initially is in a resting state, on the right side of the figure. As it reaches to grasp the cup, different numbers of fingers are used to be inserted into the handle. The three forces needed in this task are being supplied by three virtual fingers. Virtual finger 1 (VF1) is placed on top of the handle. The number of real fingers mapped into virtual finger two (VF2) depends here on the size of the handle. A third virtual finger (VF3) forms by remaining fingers to counteract the moment of the mug (from Arbib, Iberall & Lyons, 1985; reprinted by permission).

(VF1) applies a force in opposition to the index finger (VF2). For a coffee mug (Figure 2.6b), two fingers fit within the handle to form VF2, while Figure 2.6c demonstrates the case where VF2 is comprised of three fingers.

Two virtual fingers apply forces in opposition to each other, and the direction of these forces is relevant in order to clarify the type or types of oppositions. A hand coordinate frame can be placed on the palm for specifying these directions (see inset, Figure 2.7). Pad opposition (Figure 2.7a) occurs along the x axis between the thumb as VF1 and one or more fingers as VF2. Palm opposition (Figure 2.7b) occurs along the z axis between the palm as VF1 and the fingers as VF2. Side opposition (Figure 2.7c) occurs along the y axis between the thumb as VF1 and the index finger as VF2. Side opposition can also occur between two fingers.

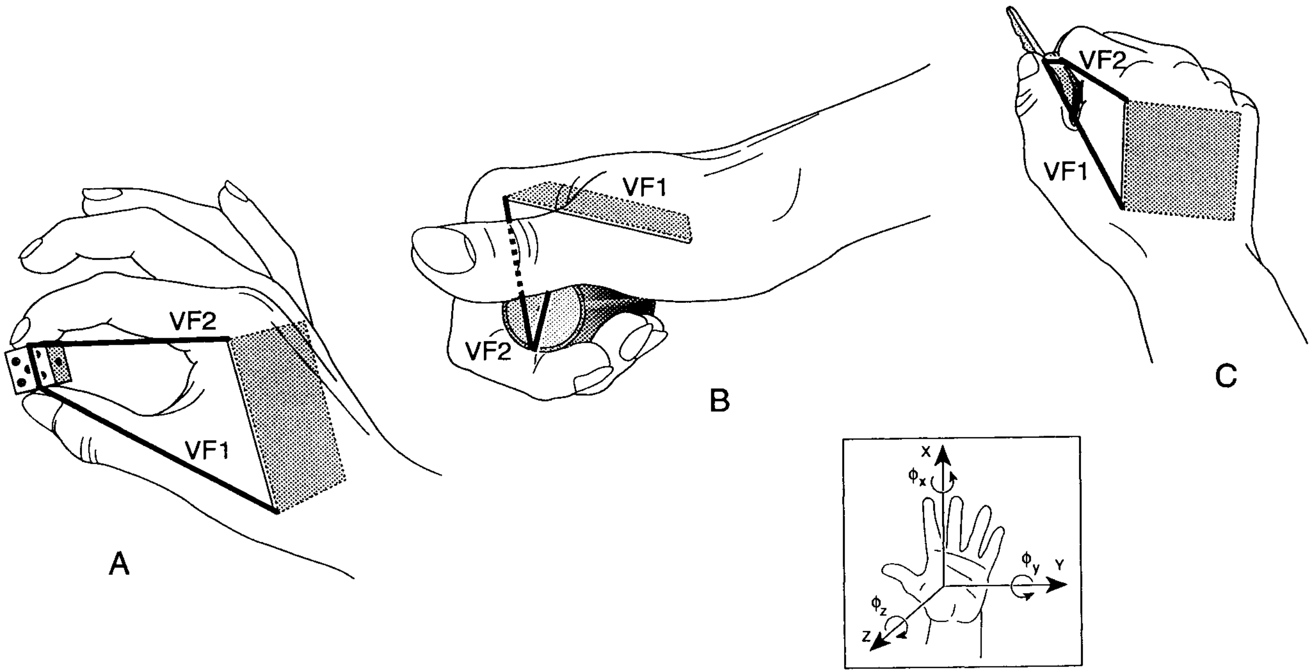

Figure 2.7 Oppositions can be described in terms virtual fingers, relative to a hand coordinate frame placed on the palm (see inset). A. Pad opposition occurs along an axis x generally parallel to the palm. B. Palm opposition occurs along an axis z generally perpendicular to the palm. C. Side opposition occurs along an axis y generally transverse to the palm. VF=virtual finger.

In terms of the prehensile classifications, palm opposition is used in the coal hammer grasp, cylindrical grasp, and spherical grasp, where the palm (VF1) is in opposition to the fingers and thumb (VF2). Pad opposition is used in precision grasps such as palmar pinch and tip prehension, where the thumb (VF1) is in opposition to one or more fingers (VF2). Finally, side opposition is used in lateral prehension, between the thumb (VF1) and the radial side of the fingers (VF2). It is also used in the adduction grip, where one digit (VF1) is in opposition to another digit (VF2).

In addition to VF1 and VF2, which apply forces in opposition to each other, a virtual finger can apply a force to counteract a task-related force or torque. This is called a virtual finger three (VF3), and it is seen in the gravity-dependent grasps. For example, a waiter holding a tray on the flat of the hand in a platform grip is using the whole hand as a VF3. Holding a suitcase in a hook grip is using the four fingers as VF3. A third virtual finger can also counteract a torque that arises in the task. For example, in the mug task (Figure 2.6), some fingers were pressed against the outside of the handle opposing the mug as it rotates into the hand. Since these fingers act as a virtual finger that counteracts a task-related torque, they are VF3.

2.3.3 Combined oppositions

Napier stressed that grasp postures showed combinations of power and precision, especially because tasks usually had both aspects, saying that 'although in most prehensile activities either precision or power is the dominant characteristic, the two concepts are not mutually exclusive' (Napier, 1956, p. 906). He pointed out that some postures exhibit both power and precision characteristics in what he called a combined grip: a precision grip (pad opposition) in the radial fingers can work in combination with a power grip (palm opposition) in the ulnar fingers. Patkin (1981) used a similar term, double grip. An example of a combined grip would be tying a knot in a cord. Tension is maintained on the cord (power activities) by the ring and little fingers, while manipulation of the knot (precision activities) is performed by the thumb, index, and middle fingers. Another example from surgery is where instruments are tucked into the palm by the ring and little fingers[9] (palm opposition) so that the radial digits can perform some other task (sensing tissue thickness or using pad opposition).

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[9]Patkin (1981) called this the ulnar storage grip.

Many postures in Table 2.1 demonstrate combined grips. One is the closed fisted cylindrical grasp with the thumb adducted (Schlesinger, 1919). As a posture used to hold beer mugs (see Figure 2.6d), the thumb is placed on top of the handle, in opposition to the radial side of the hand. This side opposition is combined with palm opposition occurring between the fingers and the palm. This is similar to the posture Napier called a power grasp (Figure 2.2a), where palm opposition (between the palm as VF1 and the fingers as VF2) is combined with side opposition (between the thumb as VF1 and the index finger as VF2). In contrast, the coal hammer version of the power grasp (Figure 2.2c) is not a combined grip, being purely palm opposition between the palm (VF1) and the fingers and thumb (VF2). Another combined grip is the dynamic tripod posture (Figure 2.4b), which combines pad opposition between the thumb and index finger with side opposition between the thumb and middle finger, while the cleft acts as a VF3. Finally, the internal precision grip (Figure 2.4c) is a combined grasp. Side opposition is used between the thumb and middle finger, and palm opposition is used between the ring /little fingers and the palm. The index finger, acting as an antenna, is a VF3.

Postures can be used as components of combined grasps. For example, an adduction grip can be used in a combined grip. Patkin (1981) described how a surgeon will at times stretch non-rigid tissue between index and middle fingers (adduction grip) and thumb and ring/little fingers (see Figure 2.4d). In this situation, the index and middle fingers are holding the tissue in side opposition, while the other fingers are using pad opposition to grasp the tissue. As noted above, a finger-as-antenna or VF3 can be used in a combined grip. For example, in the mug example (Figure 2.6), fingers pressing against the outside of the handle (VF3) are an important component of a grasp consisting of side or side/palm opposition.

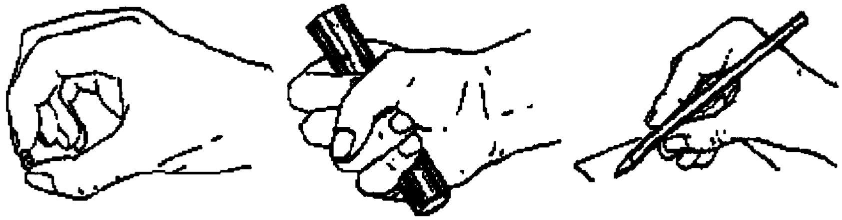
Combined grasps are seen also in holding more than one object at a time. For example, hooking a bag over the ulnar fingers as a VF3 leaves the radial fingers available for holding another object. Grasping two chopsticks is another example. Kamakura et al.(1980) called this posture a tripod grip - variation 2. This double grip holds one of the chopsticks in a dynamic tripod (pad and side oppositions as noted above) and the other chopstick in side opposition between the thumb (VF1) and the palm, ring, and little fingers.

2.4 From Classification Towards Quantification

Taxonomies are a description, using nominal levels to classify postures. In order to develop predictive models and a deeper understanding of human prehension, one must go beyond classification and description. A quantitative approach with more than nominal levels of metric is necessary. A first step crucial to this endeavor is the identification of a set of parameters that could ultimately tie into a set of important control variables. For doing powerful experimental studies of prehension, or even for developing an expert system or neural network, one needs access to quantifiable variables, or parameters. Once meaningful parameters have been identified, the next step is to develop experimental and computational models to examine the range of these parameters and their interrelations. These are necessary steps to elucidate the important control variables in prehension.

2.4.1 Encoding hand postures

Going beyond a taxonomy of grasp types, Jacobson and Sperling (1976) presented a detailed coding system which describes qualitatively the configuration of the grip of healthy and injured hands (see Figure 2.8). Focusing mainly on hand postures and based on film analysis, the code nominally labeled hand grips in terms of: fingers and other parts of the hand involved; their relative positions; finger joint angles; contact surfaces of the fingers and palm with objects; and the relationship between the object's longitudinal axis and the hand. For example, in Figure 2.8, the posture on the left is used to hold a small object between the thumb and index finger. The code for this posture is: ^{1}OMEIFM/^{2}CMFIFM. This code denotes that the thumb (finger 1) is in its opposed position (O), the metacarpophalangeal joint is extended (ME), the interphalangeal joint is flexed (IF), and the tip is in contact with the object (M). Further, the index finger (finger 2) is adducted (C) against the middle finger, the metacarpophalangeal joint is flexed (MF), both interphalangeal joints are flexed (IF), and the tip is in contact with the object (M). The coding system was computerized for larger investigations. A strength of their system is in its identification of hand surfaces involved for a given grasp type, since this can tie into how the sensory information will be gathered. Another strength is in the identification of the number of fingers and finger postures, since this ties into the application of force for a given object. Several disadvantages of their system can be observed. First, they focus on hand postures and only the longitudinal axis of the object. The coding is still at a nominal level of measurement, although it does provide a description of hand postures. In terms of using it for clinical and/or occupational evaluation of hand function, it is time-consuming and unwieldy. They provide no reliability measures. The goal of the posture is lost amidst the highly detailed coding system. Finally, although it is a small step, the system does not quantify the prehensile postures per se[10].



^{1}OMEIFN/^{2}CMFIFN D^{2345} CMFIFR/V+^{1}OMFIF ^{1}OMEIFP/^{2}CMFI*FP/^{3}MFIFS/W

Figure 2.8 Examples from Jacobson and Sperling's coding system. On the left, the thumb (1) opposes (O) with its MP joint extended (ME) and IP joint flexed (IF); the index finger (2) adduces (C) against the middle finger, with its MP and IP joints flexed (MFIF). Both tips contact the object (N). In the middle figure, the object is diagonally held (D) by the four fingers (2345) which are adduced (C) with all joints flexed (MFIF) with the more proximal surfaces making contact (R); the palm (V) makes contact; indirectly (+), the thumb (1) opposes (O) with its joints flexed (MFIF). On the right, the thumb (1) opposes (O) with its MP joint extended (ME) and IP joint flexed (IF), using the pulp (P) to make contact; the index finger (2) adduces (C) against the middle finger, with its MP joint flexed (MF) and its PIP joint flexed and DIP extended (I*F), with its pulp (P) making contact; the middle finger (3) has all joints flexed (MFIF), with its side surface (S) making contact; the web (W) of the thumb also makes contact (from Jacobson and Sperling, 1976; reprinted by permission).

2.4.2 State variables for opposition spaces

A formal language can be used to describe oppositions and virtual fingers. An opposition space provides values for a set of state vari-

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[10]The experiences with the coding scheme led to the development of a taxonomy consisting of eight postures (Sollerman, 1980). As seen in Table 2.1, this included 4 finger grasps (pulp pinch, lateral pinch, tripod pinch, and five-fingered pinch) and 4 palmar grasps (diagonal volar, transverse volar, spherical volar, and extension grip). These are similar to those already discussed.

ables that quantify a posture in both physical terms (e.g., amount and orientation of force vectors, innervation density of grasping surface patch) and abstracted terms (e.g., types of oppositions, virtual finger mappings). In terms of state variables, an opposition space is defined by the following state variables:

a) the number and type of oppositions (pad, palm, and/or side) being used,
b) the virtual to real finger mapping (i.e., which fingers),
c) VF state variables for each VF in each opposition being used, within given constraints on these state variables.

As noted earlier, postures consist of one or more oppositions. Postures can also contain a VF3 which opposes a task-related force or torque. Which real fingers are being used in each virtual finger in each opposition is called the virtual to real finger mapping.

State variables for virtual fingers can be defined as follows (Iberall, Torras & MacKenzie, 1990):

a) VF length (from the center of the grasping surface patch to the joint where it connects to the palm)
b) VF orientation relative to the palm
c) VF width (number of real fingers mapped into the VF)
d) orientation of the grasping surface patch (the orientation of the applied force)
e) amount of force available from the VF (mean, maximum, minimum)
f) amount of sensory information available at grasping surface patch (innervation density of cutaneous mechanoreceptors)

Each VF is represented by the magnitude (l) and orientation (ϕ) of a vector relative to the palm (see Figures 2.7 and 2.9); the values change as the fingers and thumb flex and extend. The VF grasping surface patch is the part of the palm or finger that comes in contact with the object in order to apply the oppositional force. A virtual finger can have a width, based on the number of real fingers mapped into the virtual finger. A simple example of a VF is the index finger used in pad opposition. Since it is being used in pad opposition, the grasping surface patch is the distal finger pulp. The VF has a length (along the straight line from the centroid of the grasping surface patch to the second metacarpophalangeal joint) and an orientation (the angle that line makes with the plane of the palm). It has a width of one because it is

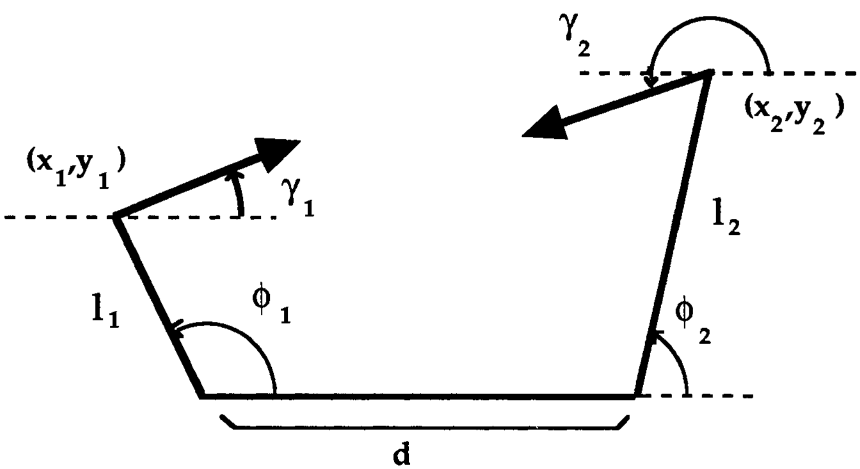

Figure 2.9. A virtual finger geometric configuration (l_i,ϕ_i) applies a force with orientation γ_i relative to the palm. The origin of the virtual finger two vector (VF2), on the right, is offset by a distance d from VF1 (from Iberall, Torras, & MacKenzie, 1990).

one finger. Using a VF2 consisting of the index and middle fingers, the width would be two. For palm opposition, the grasping surface patch for VF1 is the palm and for VF2, it is typically centered around the interphalangeal joints of the fingers, although the exact centroid is dependent on object characteristics. The width of VF2 depends on the number of real fingers being used as well as the amount of their abduction. In side opposition, the grasping surface patch for VF1 is the thumb pad and for VF2, it is typically the radial aspect of the index finger near the interphalangeal joints.

VF vectors are tagged with the orientation γ of the grasping surface patch relative to the palm at a given configuration (see Figure 2.9). In the index finger example, as the VF vector changes length (l_2) and orientation (ϕ_2) during flexion and extension, the pad changes orientation (γ_2) relative to the palm. The VF1 configuration (l_1,ϕ_1) has an orientation (γ_1) as well. Each VF must also be able to apply forces and gather sensory information. The amount of force that the VF can apply depends on the configuration of the finger and the underlying biomechanics. As will be seen in Chapter 6, the largest forces are available in palm opposition, followed by side opposition and then pad opposition. In terms of sensory information, high densities of mechanoreceptors have been noted in the finger pads, as also will be seen in Chapter 6.

VF state variables must obey their own constraints. For a task using an object of width w, height h, and with a minimum force to be applied p, the following constraints must be obeyed:

a) Finger Position constraint. The distance between the grasping surface patches of the two VFs must be w (the object width).
b) Force Magnitude constraint. The minimum force, p, necessary in the task must be smaller than the maximum force that can be applied by the VFs. The magnitude of the force applied by the two VFs must be equal.
c) Finger Width constraint. The object length h can represent an upper limit on the width of a VF (e.g., coffee mug handle vs. coin held in palm).

Within an opposition, state variables must also obey constraints. Given an opposition, the following constraint must be obeyed:

d) Force Orientation constraint. The two force orientations γ_1 and γ_2 must align with each other during the opposition. From Figure 2.9, $\gamma_1 = \langle\gamma_2 + p\rangle_{2\pi}$.

Setting up an opposition space in effect fixes certain degrees of freedom while making others the variables for the task. The usefulness of this model is that it reduces the complexity of the sensorimotor problem. The style of posture chosen matches the task requirements with the hand's capabilities. In pad opposition, the hand can exert small forces, impart fine motions, and gather precise sensory information to match the accuracy and manipulation requirements of the task. In palm opposition, the hand can match or create larger anticipated forces while still ensuring a stable grasp, using the arm and wrist to provide grosser motions. Side opposition is a bridge that offers a medium range of forces while still offering some availability of sensory information due to the thumb pad being in contact with the object and some ability to impart motions to the object. Using the mathematical description provided here, a more quantifiable notion of power and precision capabilities is possible. As a parameterized view of human prehension, this model provides components for modeling a biological subsystem for the control of natural, prosthetic, and robotic hands. The abstracted description of opposition space in terms of required opposing forces, virtual fingers and state variables allows for modelling and control of natural, prosthetic and robotic hands.

2.5 Summary

Beginning with an overview of prehension and grasp classifications, the essence of these typologies has been searched. In so doing, the importance of more detailed information about prehensile postures was identified, based on the hand, object, and task characteristics. The black box introduced in Chapter 1 mapping object and task characteristics to prehensile behaviors can be looked at with a finer level of detail (see Figure 2.10). Objects come in a variety of shapes, sizes and surface characteristics, and tasks have constraints on their spatial degrees of freedom. In order to achieve the task goals with these objects, the hand is used to apply forces, impart motions as necessary, and gather sensory information. Prehensile postures can be described either using the terminology of the classifications listed in Table 2.1, or else in opposition space terms. Schlesinger identified hand surfaces and shapes that combine with object characteristics to name possible ways that the hand, in effect, creates tools for prehension. He pointed out how the hand can grasp arbitrary objects. Napier introduced the notion of task features, noting that the power and precision requirements of tasks could be met by the power and precision capabilities of the human hand. Landsmeer focused on the dynamic aspects of grasping and contrasted precision handling with power grasp, noting the manipulative options are afforded by opposing the pads of the thumb and fingers. Kapandji gave examples, such as turning, squeezing, and cutting, and Elliott and Connolly provided a vocabulary to expand on this notion (twiddling, rocking, rolling, stepping, sliding). Other researchers, studying the hand from anatomical, occupational, disability, and robotics perspectives, have identified unique sensorimotor features of the hand that are exhibited in the link grip, the hook grip, the three-jaw chuck, the dynamic tripod, the adduction grasp, and the finger-as-antenna. The Opposition Space model suggests that, in all these postures, the hand is applying oppositional forces against task forces and torques and/or around an object along three general directions, either alone or in combinations. This extensive multidisciplinary research provides insights into the functionality of the human hand, based on three issues: applying forces to match the anticipated forces in the task, imparting motion to the object as necessary, and gathering sensory information about the state of the interaction with the object.

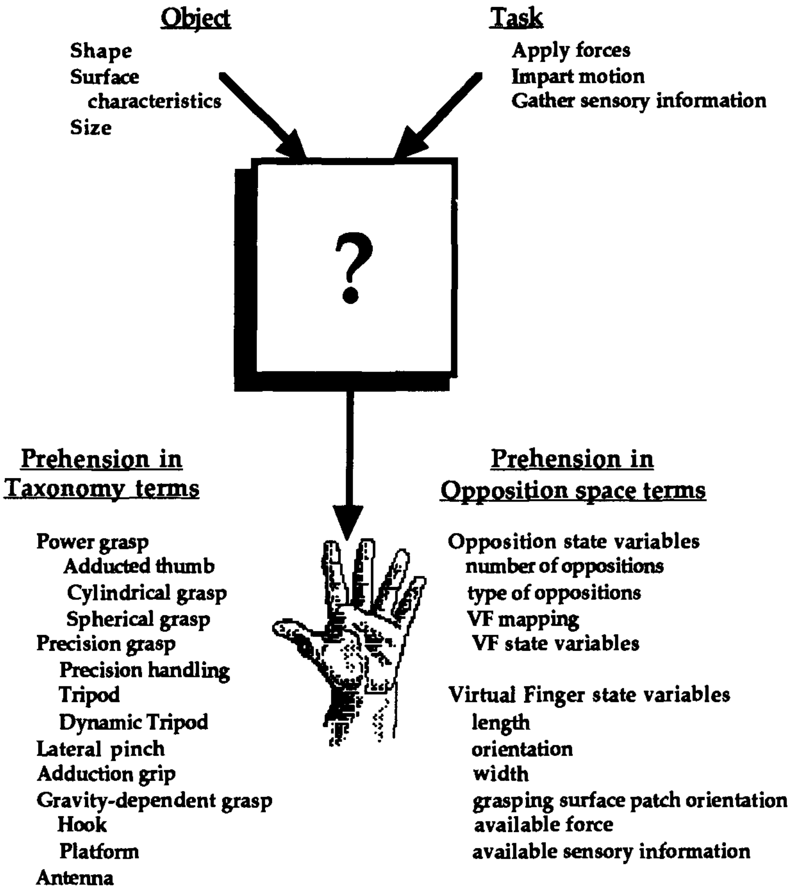

Figure 2.10. Mapping between Object, Task, and Prehensile behaviors. Specific object properties affect the chosen posture. Task requirements of applying forces, imparting motions, and gathering sensory information can be matched by the functional capabilities of the hand. Prehensile postures can be described either in opposition space terms or according to the classifications.

In pad opposition, the hand can exert small forces, impart fine motions, and gather precise sensory information to match the accuracy and manipulation requirements of the task. Landsmeer's extension to Napier's classification made clear this dynamic component of precision; i.e., imparting motion to the object by the fingers. A combined case of pad and side opposition occurs when the thumb opposes the index and middle fingers. The unique relationship between the thumb, index, and middle fingers creates a powerful tripod, much like a three-jaw chuck of a drill, for both stabilizing an object and manipulating it. For longer objects, resting the object against the cleft of the finger adds a fourth surface for counteracting task torques. This in effect is a third virtual finger, because it is not opposing another virtual finger.

In palm opposition, the hand can match or create larger anticipated forces while still ensuring a stable grasp, using the arm and wrist to provide grosser motions. Two aspects to note for palm opposition that have caused much speculation in taxonomies are the thumb position and the shape of hand. In terms of position, the thumb can either contribute to the opposition (Napier's coal hammer grasp) or act as an antenna (Schlesinger's closed fist with adducted thumb). In terms of hand shaping, the palm and fingers can wrap around objects symmetrical about an axis (Cutkosky's prismatic grasps and Schlesinger's cylindrical grasp) or the palm can arch around objects with radial symmetry (spherical or circular grasp).

In side opposition, the thumb pad is brought against the object in opposition to the radial side of a finger. As a bridge between power and precision grasps, this posture offers a medium range of forces while still offering some availability of sensory information due to the thumb pad being in contact with the object and some ability to impart motions to the object (as in turning a key). Mentioned by a majority of the classifiers, the functionality of side opposition again rests in the anatomy of the hand: pronation and supination at the wrist can be used to rotate the object being held in a secure grip by the thumb and radial side of the index finger. A special case of side opposition is seen in the adduction grip that allows the same object manipulation (pronation and supination of the wrist) at the expense of applying forces and gathering sensory information (no distal pads or extrinsic hand muscles are used to create the oppositional force). However, motion can actually be imparted to the object, since finger flexion and extension can be used.

A third virtual finger can apply a force against gravity, can impart motion mostly with the arm or wrist, and can gather sensory information using sensors in the hand surfaces to determine the state of the object. Most taxonomists mention the hook grasp, but others like Kapandji and Cutkosky generalize the hook to the notion of gravity-dependent grasps. Extending a finger (usually the index) as an antenna is an excellent way to enhance the availability of sensory information (due to the large number of mechanoreceptors in the finger pads and interphalangeal joints). Although it reduces the number of fingers available for applying forces, the extended finger in itself can apply a limited force, provide direction and impart some motion as necessary for a VF3. Importantly, it can be used in combined grasps, as seen in extending the index finger on a screwdriver or knife, or placing the thumb on the side of a beer mug.

The key to understanding the versatility of the human hand is not so much that it can create any one of these postures, but that it can also do these in combinations[11]. While using the dynamic capability and sensitivity of the three radial digits in pad or pad and side opposition, the other two fingers can still oppose the palm, grasping an object in palm opposition. The surgical techniques described by Patkin are some examples of this ability of the human hand to hold (and even manipulate) more than one object at a time. An antenna can be formed by the extended index finger or adducted thumb that acts both as a receiver of sensory information and a transmitter of forces as needed. At the same time, the other digits can create the stable grasp, as seen in Figure 2.2 and Figure 2.4. Examples of functional combinations were seen: in grasping a mug where side opposition combines with VF3; in the internal precision grip where palm opposition combines with side opposition and a VF3 as antenna; and a double grip, where side opposition occurs between the index and middle fingers and pad opposition is used by the other digits. Napier's power grasp, in fact, combines palm opposition with side opposition. An example of using these multiple functional features to hold more than one object at a time was seen in grasping chopsticks. Ultimately, the versatility of the human hand stems from what Napier pointed out in 1956, that precision and power are not mutually exclusive. The human hand (and brain!) can resolve these multiple task components and in doing so, find a set of oppositional forces that are functionally effective for satisfying the competing task requirements for arbitrary objects. And this is true whether the task is to hold one or even 10 oddly-shaped objects at a time, and whether the task is to do either one or many things with them!

For Napier, the terms power and precision grips were intended to be used to describe the whole hand in the dynamic as well as the static sense, just as the terms flexion and extension can describe movement or the static posture about a joint. However, he suggested that, "it is

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[11] In Appendix B, a table listing most of the possible combinations of oppositions and virtual finger mappings can be found.

impossible to treat these phases biometrically" (Napier 1956, p. 913). With the technology of the 1990s, it is both possible and desirable to capture biometrically the dynamic versatility of the human hand, through phases of prehensile movement. The next section addresses these issues.

Part II

THE PHASES OF PREHENSION

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Chapter 3. Serial Order in Prehension

"Movements have the teleological property of anticipating targets in space and time and can be fluently coordinated to realize a given schedule."

--Shaffer (1982, p. 112)

A hammer sits on the table in front of you. You reach out, pick it up, and place it on a shelf. What was involved in this task of picking up the hammer and placing it?

Woodworth (1899) first described goal-directed aiming movements as being two-phased: an initial, ungoverned motion, followed by a final, currently controlled adjustment. The initial adjustment phase transports the limb quickly towards the target location, and the current control phase subsequently corrects any errors made along the way, using sensory feedback to reach the target accurately. These findings have been reported consistently, and extended in the literature since the time of Woodworth (for a comprehensive review, and discussion of the speed accuracy tradeoff in aiming movements, see Meyer, Smith, Kornblum, Abrams and Wright, 1990).

The notion of two phased movements was introduced into the grasping literature by Marc Jeannerod (1981, 1984). In 1981, Jeannerod published seminal data suggesting that two phases were occurring during prehensile movement. He performed experiments in which subjects grasped small objects such as rods, cylinders, and spheres. These movements were made in the sagittal plane. Based on cinematographical analyses of the positions of the index finger and thumb during the grasping of objects, he suggested that there was a fast (high velocity) phase and a slow (low velocity) phase. Figure 3.1 shows some of Jeannerod's results. Jeannerod based his analyses on the transport of the hand which can be seen in the top of the figure showing results for two different sized objects, and the shaping of the fingers into an aperture between the thumb and index markers, which can be seen in the bottom of Figure 3.1. The first phase of the movement, from initial movement to peak deceleration of the wrist, lasts for approximately 70% of total movement time. It is important to note that the tangential velocity profile is bell shaped but asymmetrical. During this fast high velocity phase, the hand was opening as the fingers were extending, thereby posturing appropriately for the grasp.

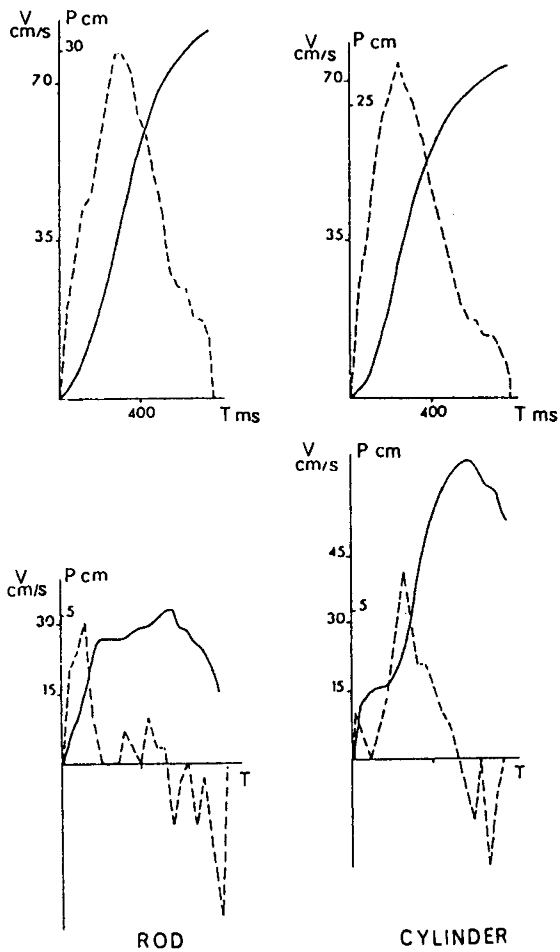

Figure 3.1 Wrist velocity and aperture profiles for grasping two different sized objects. Top row: Transport component on the left for a small rod (2 mm in diameter) and on the right for a large cylinder (5.5 cm in diameter). Lower row: Manipulation component for the same two objects. Solid line represents position and dashed line represents the velocity profile (from Jeannerod, 1981; reprinted by permission).

The peak aperture of the grip was reached at about the same time as peak deceleration, at about 70% of the total movement time. During the slow second phase, Jeannerod noted many corrective type movements in the transport, as the hand enclosed around the object.

Jeannerod (1984) made an important observation, often forgotten or ignored, that these corrective type movements occurred during the deceleration phase even when only the target and not the hand was visible. He thus concluded that the slow phase was not due to visual feedback processing but was a centrally generated part of the prehension pattern, a positioning or target acquisition phase. To summarize, Jeannerod hypothesized that reaching and grasping movements can be separated into two phases: an initial, faster arm movement during which the fingers preshape, and a slower arm movement beginning after maximum aperture, during which the fingers enclose to make contact with the object.

Interestingly, Jeannerod (1984) reported a temporal coupling as revealed by correlations between the time of peak deceleration of the wrist and the time of peak aperture of the grip. Figure 3.1 shows that the time of maximum aperture corresponds with the onset of the low velocity phase. Jeannerod argued that the arm, which is the transport component carrying the hand to a location, is controlled separately from the hand which is the manipulation or grasp component shaping the hand in anticipation of the grasp. Further, these are temporally linked for the coordination of prehensile movement. He hypothesized a central program or pattern for the coordination of the transport component with the manipulation (or grasp) component of the unitary act. Jeannerod suggested that "the synchronization of the low velocity phase with finger closure indicates that both are controlled by a common program which achieves the timing of coordination" (1984, p. 253).

With regard to the transport and grasping components, Jeannerod presented systematic differences in the effects of object properties on reaching and grasping. He contrasted conditions in which subjects grasped small or large objects, such as rods and cylinders, with conditions in which subjects had to move to different amplitudes in the sagittal plane. As seen in Figure 3.2, distance of the object away from the subject affected the transport component (peak velocity increased with the distance to be moved) but not the grasping component. Conversely, Figure 3.2 shows the object size affected the grasping component (maximum aperture was bigger for a larger object), not the transport component. Jeannerod made an important distinction between intrinsic object properties (identity constituents such as size,

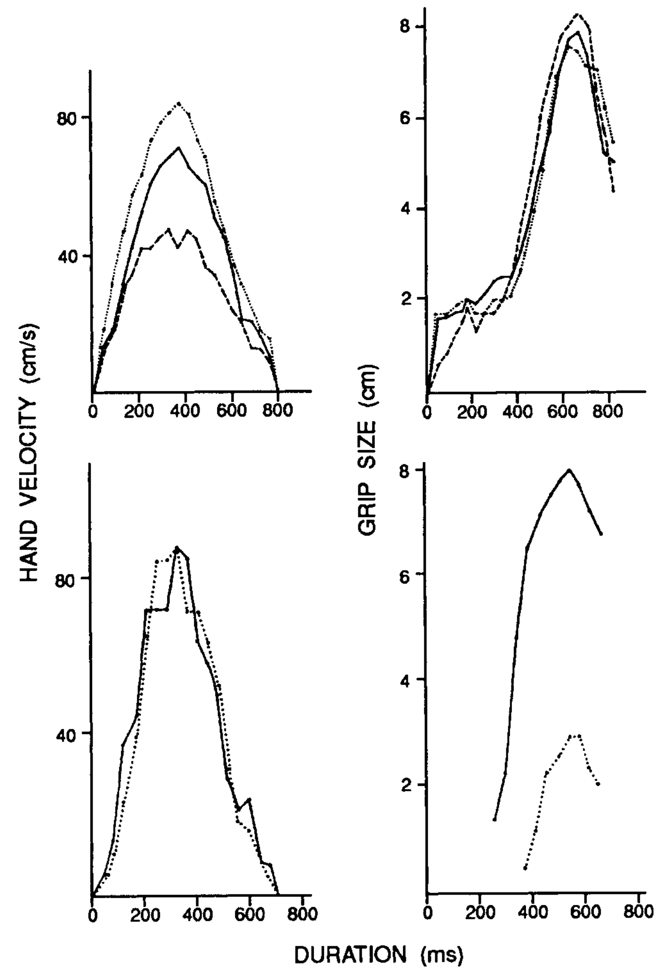

Figure 3.2 Wrist velocity and aperture profiles for grasping as a function of distances and object size. Top row: The subject reaches out to grasp an object of constant size at three different distances away. On the left, the velocity profile shows a systematic increase with distance. On the right, no difference is seen in the aperture between the thumb and index finger. Lower row: The subject reaches to grasp two different width objects with the left and right hands, in a bimanual task to remove a plug from a bottle. On the left, no difference is seen in the velocity profiles. On the right, a difference is observed in maximum size of the apertures (from Jeannerod, 1984; adapted with permission).

and shape) and extrinsic object properties (or egocentric spatial properties such as distance, orientation, direction and velocity of object motion with respect to the body). He suggested that the two types of properties are likely to be detected through different structures or channels. Specifically, he suggested that for grasping an object, separate visuomotor channels are activated in parallel by a specific visual input and controlling a specific part of the limb musculature. For example, extrinsic spatial properties of an object activate proximal muscles (e.g., shoulder joint) for the transport component, and intrinsic properties activate distal segments (e.g., fingers) for the grasping component.

3.1 Conceptual Models of Prehension

Arbib's conceptual model (1981) of a coordinated control program for grasping captured the data of Jeannerod. In the 1985 version, seen in Figure 3.3, perceptual schemas in the upper half of the figure extract relevant task related information from the environment. The perceptual schemas serve as identification algorithms (procedures) to determine parameters for motor schemas, seen in the lower half of the figure.

The perceptual schemas include a visual location schema which, when activated, in turn activates size recognition and object orientation recognition schemas. The motor schemas control some aspect of the movement. Perceptual and motor units all working together, not under one central controller, but under distributed control. On the left half of the figure are depicted motor schemas controlling the arm for the reaching, or transport, component of the movement. Visual information about object location provides data to the hand reaching schemas. Jeannerod's high velocity phase has been labelled as a 'ballistic movement'. The low velocity phase after peak deceleration has been called 'adjustment' by Arbib. Motor schemas in the right half control the grasping component. Visual information about object size and orientation provide data for the grasping schemas. The fingers change their posture, making adjustments or preshaping into some suitable shape. The hand is rotated into a suitable orientation as well. Activation of the motor schemas simultaneously initiates ballistic movement to the target and a preshaping of the hand. The fingers are adjusted to the size of the object and the hand is rotated to the appropriate orientation. Ending the ballistic movement of the wrist gives rise to activation of the 'actual grasp' schema whereby the fingers are

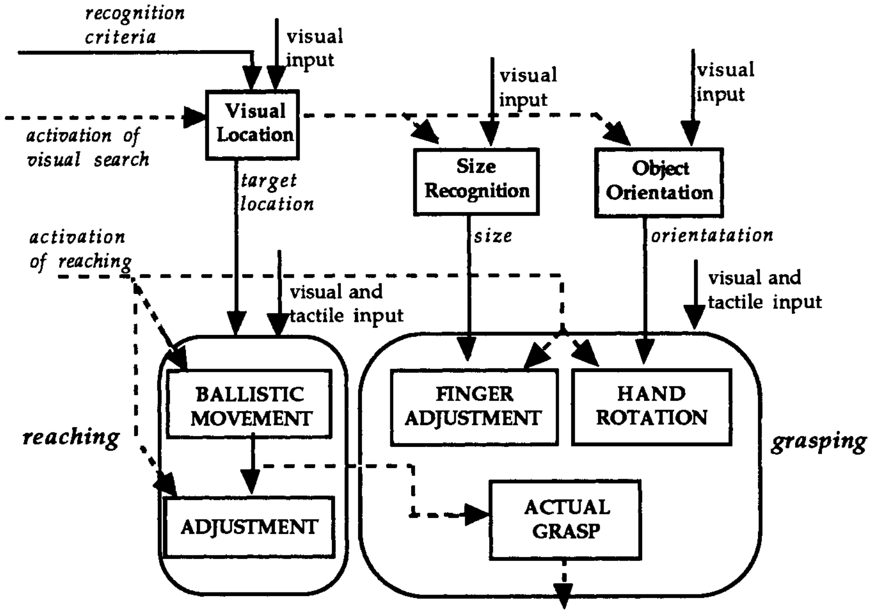

Figure 3.3 Coordinated control program for reaching and grasping. Perceptual schemas, on the top, extract relevant task information from the visual scene. Motor schemas, on the bottom, perform the transport component (on the left) and the grasping component (on the right). Grasping involves adjusting the hand posture and orienting the wrist. The differential effects of visual and tactile inputs on motor schemas are unclear in this model. Solid lines represent data lines, and dashed lines represent control lines (from Arbib, 1985; adapted by permission).

enclosed around the object. On contact with the object, the actual grasp occurs.

Based on the results of experimental investigations of the role of vision in reaching and grasping (research on humans, split brain monkeys, and prismatic displacement), Paillard (1980, 1982b) also presented a schema model which segmented reaching behavior into several temporal phases via two parallel visual channels performing object identification and object location functions. Figure 3.4 indicates that after the eyes and head are positioned for foveal grasping, there are triggered (open loop) and guided (closed loop) phases for the arm and hand. A location channel uses movement cues from peripheral vision for transporting the arm (assisting the 'navigator') and in parallel, an

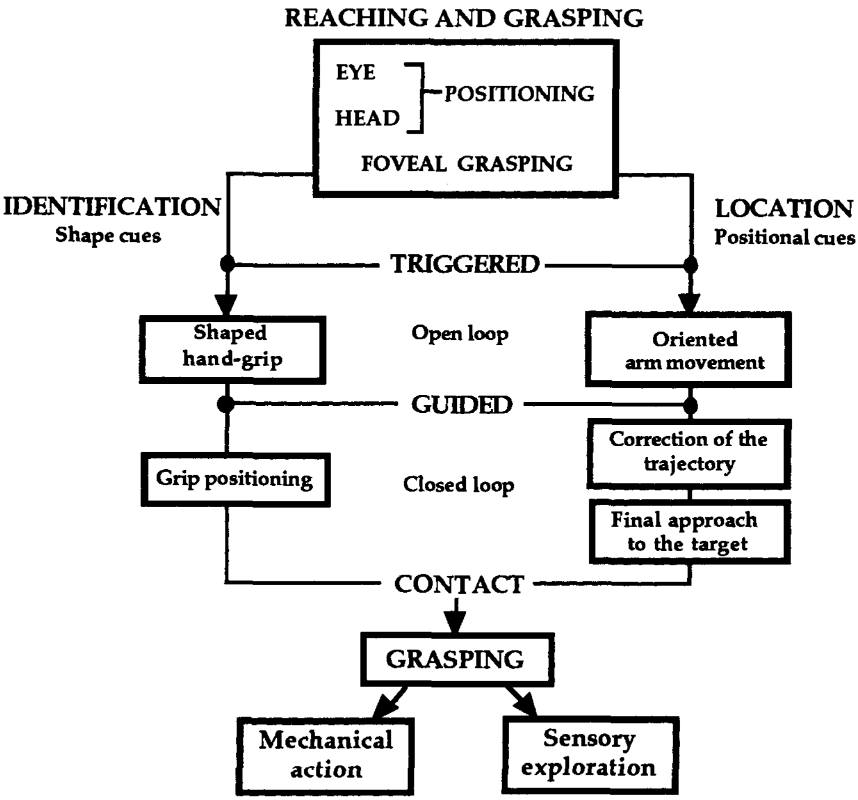

Figure 3.4 Paillard's model of reaching and grasping. Functional segmentation of reaching behavior is divided into two parallel visual channels subserving identification and location. Visually triggered programs presetting the hand grip and orienting the arm movement might be assisted by visual guidance of grip positioning and of trajectory in its initial and final stages. Tactile cues then become prominent to assist manual grasping after contact with the object is established (from Paillard, 1982b; adapted by permission).

identification channel uses shape cues from central vision for the formation of the hand grip (assisting the 'pilot'). Contact with the object ends the parallel processes of visual location and identification, leading to tactile guidance of grasp, after which follows sensory exploration and/or mechanical actions with the object.

An alternative model to the distributed ones of Jeannerod, Arbib,

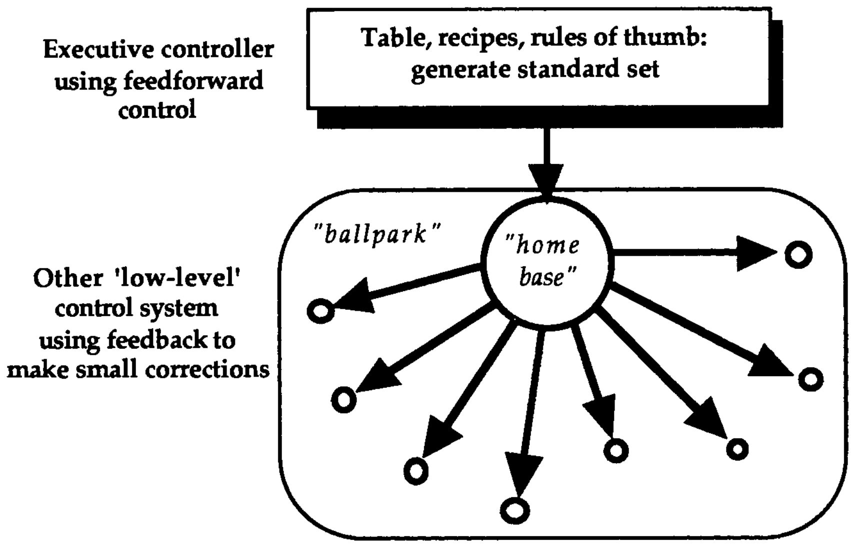

Figure 3.5 Greene (1972) notion of 'ballpark'. The executive selects an appropriate combination that is 'in the ballpark' of the correct movement; the lower centers refine this approximation closer to the desired movement.

and Paillard is a hierarchical system, where central, higher centers set up some motor commands that are then transformed by lower centers (Brooks, 1979; Keele, 1981). Greene (1972, 1982) suggested that the nervous system has a few degrees of freedom, but it governs subsystems having many degrees of freedom, much like a puppet master with a marionette. To do this, using a hierarchical organization, an executive brings together combinations of movements that are constrained by lower-levels. Shown in Figure 3.5, the executive selects an appropriate combination that is 'in the ballpark'[1] of the correct movement; lower centers refine this approximation closer to the desired movement. In effect, by locking some joints, the executive is 'assembling a virtual arm'. Greene made an interesting analogy to an

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[1] The ballpark analogy is derived from the American game of baseball, referring to the notion of being within the area of the baseball field. Similarly, one might think of a soccer field as defining the soccer workspace.

army, where the general issues the goal for the troops without specifying the individual movements of all the soldiers. An important point is that there is a limit to the set of commands that the general has available; thus, the general may be powerful, but this power exists with respect to a limited collection of troop activities (which in themselves might be quite complex). While Greene stressed a hierarchical interaction between 'executive' and 'low-level systems', he argued that their relationship could change; perhaps it would be more appropriate to view this as a heterarchical or distributed model.

Greene's model suggests that the executive acts in a feedforward manner to bring the system into a class of states, or 'into the right ballpark', as seen in Figure 3.5, so that feedback can be used to make the small remaining corrections. This reduces the complexity of the control system, but it also reduces generality, because not every possible response can be made. The executive computes the parameters to tune low-level mechanisms, which can continue to produce reasonable responses even without further communication until the next update. The executive can run a speeded-up model of the controlled system's behavior, and thereby predict the results of actions. Greene suggested that the brain stores recipes or formulae for generating functions that map commands into states and transformations of states for low-level mechanisms. Thus, there is a separation of responsibility between standard activation and fine-tuning of the motor command. Greene argued that the executive need not even be aware of the tuning. In Greene (1972), he argued that the process acted as an approximate feedforward system, which is corrected by feedback. For example, when a cat stands on a perturbed platform, its vestibular system must increase the tension in each supporting muscle so balance is maintained. An exact computation would be too slow, but a rule of thumb would increase the tension in the muscles that are already exerting the most support. While not exact, feedback can then be used to make small corrections. However, the vestibular response is not appropriate when the cat shakes his head; instead of a lack of response in the vestibular system, its response is just nullified by neck muscle receptors. In grasping, Traub, Rothwell, and Marsden (1980) reported a 'grab reflex' or 'sherry glass response' whereby, regardless of loading or unloading of the thumb flexor muscle (flexor pollicis longus) by mechanical perturbations to the wrist, a functional response is to maintain grasp. This is dependent and adapted to the task and the intent of the individual, which in this case is to maintain the digits in contact with the object. For example, on board a rolling boat, one instinctively grabs for a falling wine glass. This grab reflex is not voluntary but depends on the person's intent. If one chooses to ignore the fragility of the object, there will be no response.

The power of conceptual models like Arbib's, Paillard's, and Greene's is that they provide a summary of what is known and a starting framework for detailing the planning and control processes. Their validity can be argued from the fact that they are based on experimental evidence. They rely on perceptual and motor units all working together, not under one central controller, but under distributed control. They also represent plausible views which in turn suggest testable hypotheses about central nervous system (CNS) mechanisms, planning and control algorithms for such a complex behavior as reaching and grasping.

Conceptual models are useful as a starting ground for understanding the complex interaction between a performer and the environment. Sensory information is needed at crucial times for completion of the motor task. The CNS, however, being highly parallel and redundant, can solve problems in many ways. It exhibits motor equivalence, in that motor commands are nonspecific and different spatial-temporal patterns of action can produce the same outcome. Muscles can vary their functional roles from movement to movement. It has been shown that handwriting, for example, is the same regardless of the writing implement, speed, size, or limb used. Another issue is the availability of sensory information. If available from a given modality, it has the potential of being used in the control of the movement; if not, other modalities of sensory information will be used. If visual information is available, it will be used, causing movements to be slower. If not, subjects rely more on touch. Finally, an important issue in studying human motor control is the fact that there is a great deal of variability in movements. Seemingly identical movements are not exactly alike. However, these variations occur within a restricted bandwidth. As a result, one approach to studying motor control is to examine the variability of movements (Marteniuk & MacKenzie, 1990; Newell & Corcos, 1993; Worringham, 1987,1991).

When our 'triangular' modelling strategy was introduced in Chapter 1 (Figure 1.3), it was noted that existing models suggest further experiments, the results of which might suggest more comprehensive models. Since Arbib's conceptual model first appeared in the literature, experimental evidence has shown that size information not only affects the grasping component but also the transport component. Recent experiments indicate that visual and mechanical perturbations affect the kinematics of the transport component as well as the manipulative or grasping component. This suggests a functional coupling of transport and grasping components. Research that restricts visual information to the central or peripheral visual fields shows differential effects on the transport and grasping components, thereby extending the distinctions made in Paillard's conceptual model.

Significant limitations to these conceptual models relate to the underlying question of the sequencing of phases. Jeannerod's analyses were strictly limited to movement before contact with the object, yet he also argues for the separation of this movement into two distinct phases. As Paillard (1982b) anticipated, and others have experimentally demonstrated, there are obvious differences in the movement before and after contact with the object. For example, multiple phases of force application have been identified after contact with the object. As well, much has been written in the robotics literature about stably grasping and manipulating objects. A more comprehensive model must be developed to reflect current knowledge of the entire complexity of grasping movement.

For the modeller, the conceptual model does not explain exactly what information is being transferred or controlled. What are the inputs and outputs? For example, what is the size information being passed to the 'finger adjustment' schema, and what exactly does it mean to adjust the fingers? Many researchers, such as Jeannerod, have looked at the aperture between the thumb and index finger as a metric of hand shaping. Is this a valid metric, or are there more revealing, complete methods for quantifying hand shaping? In light of the prehensile classification schemes outlined in Chapter 2, the size of the aperture may be a reasonable measure for pad opposition, but is it valid as a measure for other grasps involving hand surfaces other than the fingers pads?

Two main messages can be seen in Jeannerod's results and the conceptual models of Arbib, Greene, and Paillard. First, the system is a distributed one, involving parallel activation and coordinated control of several components or subsystems. In addition to the transport and grasping components, parallel activation and control of head and eye movement occurs in order to foveate objects. Likewise, there are corresponding postural adjustments to optimize interaction with the object and maintain stability or balance. While all these subsystems are important, this book concentrates primarily on the transport and grasping components. The second main message is that there are different phases as the unified act of grasping unfolds. The problem of serial order in behavior has long been of interest (see Lashley, 1951). Detailing the phases of prehension at a conceptual level, based on existing evidence from experimental and computational models, will further our understanding of prehension.

3.2 Derivation of Criteria for Defining a Phase

At certain times throughout a prehensile task, unique events take place. Each one may be viewed as a phase. The criteria for defining a phase are crucial. Evidence for the existence of different phases can be derived from:

1) Motor characteristics: Analysis of motor characteristics involves various kinematic and kinetic features and invariances, movement precision and outcome, and electromyographic (EMG) recordings. For example, movements can be identified as being ballistic, corrective, or tracking. Is the function of these movements to get in the 'right ballpark' or precisely 'home in'? Where possible, relationships among kinetics, kinematic features/invariances, EMG, and outcomes with respect to task related goals are examined. Important issues to consider include the coordinate frame in which the movement occurs and whether feedback or feedforward control might be at work. In addition, the level of the motor command must be considered (e.g., muscle level, movement level).
2) Sensory information: Sensory information is analyzed by type of information available, by its modal characteristics, its frame of reference, and by the time needed to influence motor characteristics. If multiple modalities are available, how do they interact? Possible influences of sensory information are examined in terms of lag time to elaborate models of sensorimotor integration. The influence of motor on sensory systems and vice versa is acknowledged for goal-directed movement. We emphasize the importance of vision prior to contacting the object. Once contact is made with the object, the role of touch becomes critical. Important to the initiation of a phase are the events that possibly trigger it, and important to control issues is the nature of sensory feedback.
3) Intent: Intent determines movement and apparent anticipatory behaviors, which is why it is suggested here that the movements of grasping are teleological. This is related to the individual's understanding of task and goals. In terms of control, in certain phases, a subgoal may dominate a goal; e.g., maintain stability if an object is slipping from grasp. Subgoal dominance probably

would be accompanied by sensory, motor and sensorimotor evidence.

4) Context: Memory of past experiences implies a central representation, opposing the notion of purely dynamical reasons for movement. This implies the presence of memory buffers that could be affected by previous phases or previous conditions, such as stability of grasp which is an underlying goal of prehensile movement. With this view of memory, the motor system is neither a slave to the dynamics, nor a slave to cognition.
5) Neural events: Underlying neural events include response characteristics of various neural substrates. If neurophysiological and neuropsychological evidence indicates that certain brain areas are active or crucial at a given time and not at other times, then this is converging evidence for a different phase of the movement.

In contrast to a reductionist approach, the focus here is on sensorimotor integration processes, which are more than the simple sum of the motor and the sensory components. Our goal is to present a holistic approach, based on perception-based action and action-based perception, achieved through multiple levels of sensorimotor integration.

The prototypical task introduced at the beginning of the chapter is now more formally described. A subject sits at a table, with a hammer on the table directly in front of her midline. The heel of her hand is resting on the table and her forearm in semi-pronation. Her eyes are closed, until a signal is given. She is told that she will grasp the object to place it on the shelf. On the signal, she opens her eyes and performs the task. Such a task requires the coordinated activity of almost the entire body: trunk, eyes, head, neck, arms and hands. The task requires the serial unfolding of a number of unique phases. Prior to movement, there must be some planning. Movement begins and the anticipatory shaping of the fingers is seen, appropriate for the task at hand, as the limb moves. Then, the fingers begin to enclose around the hammer. After initial contact, the hand captures the object, establishing a stable grasp. The object is then lifted and transported to a location above the shelf. The hammer is then placed on the shelf, and released by the hand.

For the remaining chapters of Part II, we now turn to a more detailed consideration of the serial unfolding of prehensile activity.

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Chapter 4. Planning of Prehension

"The introduction of motivation (drive or will) and corresponding planning is one of the major points of the modern theory of voluntary movement."

--Kornhuber (1984, p. 165)

plan: *v.t.* 1. to make a plan of (a structure, piece of ground, etc.). 2. to devise a scheme for doing, making, or arranging. 3. to have in mind as a project or purpose. From the Latin *planus*, plane, level (Webster's New Twentieth Century Unabridged Dictionary, 2nd Edition.)

A subject sits in front of a table, with a hammer directly in front of her midline. Her hand is resting on the table, slightly pronated in the position of rest. Her eyes are closed, until a signal is given. She is told that she will grasp the hammer to place it on the shelf. On the signal, she will open her eyes and perform the task. Yet, even though the signal to begin the task has been given, there is a delay before actual movement towards the hammer begins. Why is there a delay and what is happening during this time?

This chapter focuses on the preparatory processes related to the organization and planning of the upcoming movement. The CNS makes plans for moving the hand to some location in space near the hammer (in a specific direction, for a specified distance), for orienting the hand relative to the hammer (defining contact locations), and for grasping it in accordance with the task of placing it on the shelf (with functionally effective forces of a given direction and magnitude). In choosing an opposition space useful for the task, this planning process involves three aspects:

1) perceiving task-specific object properties,
2) selecting a grasp strategy, and
3) planning a hand location and orientation.

Choosing an opposition space useful for the task depends on information perceived about the object, such as its location and its intrinsic properties. The particular properties perceived are task-related. For example, color is not particularly useful for grasping, other than helping to distinguish features of the object. But perceived size, weight, and shape are useful. In addition, through years of experience, we have acquired knowledge about how objects can be expected to behave when we grasp them, a field of research called 'task mechanics'. The term 'grasp strategy' refers to selecting appropriate opposition types, mapping virtual fingers into real, anatomical fingers, and determining opposition space parameters to achieve a hand configuration and aperture appropriate for the task and object at hand. Selecting a strategy is quite dependent on a person's anatomy, emotional state, intentions, fatigue level, motivations, etc. Planning a hand location and orientation will depend on the grasp strategy chosen. Before any movement occurs, a sensorimotor set is established, 'tuning' the spinal circuitry and motoneuron pool, allowing for gating of sensory information and motor outputs.

4.1 Types of Planning

The nature of plans and programs has been of central debate in psychology, physiology, movement science and computer science. Miller, Galanter and Pribram (1960) suggested that plans have time scales, i.e., life goals, yearly plans, daily plans through to the plans for imminent movements. As the time frame shrinks, there are differences in the nature of goals and the levels of analysis for procedures to achieve those goals. Life plans are abstract, while upcoming programs of action must be more specific and concrete. In the analysis of human motor behavior, views on the issue of motor planning are diverse and heated. At one end of a continuum, there are those individuals who would deny any central representation for movement (e.g., Kugler, Kelso, and Turvey, 1982). Called direct or action theory, this approach appeals to physical, deterministic, environmental and dynamical levels of explanation, and denies the relevance of concepts such as intention, learning and memory. In contrast, there are those who would posit a central representation or motor program to specify the details of an upcoming movement (see Keele, Cohen & Ivry, 1990). For reviews of the debates concerning physical and representational analyses of human movement planning, see Whiting, Meijer, and van Wieringen (1990); for related discussions on the interface between the neurosciences and cognitive sciences, refer to Churchland (1989).

For our purposes in this book, we are concerned with representation and computation by the CNS or another computational system in the planning of prehensile movements. Planning is discussed at two different levels. One is concerned with the movement process (how to execute the movement, from the perspectives of kinematic analyses of the motion, kinetic analyses of muscle/joint forces and torques, or muscular innervation). The other concerns the movement product or goal of the action. Using the terminology of Schmidt (1988), the environmentally defined goal (e.g., placing a mug in a dishwasher, throwing a basketball through a hoop, grasping a hammer) is the task. In movement sciences, the distinction between movement process and movement product has been a valuable one (Gentile, 1972; Schmidt, 1975, 1988).

Parallel to movement process and movement product, a distinction is made in robotics between trajectory planning and task planning. Trajectory planning is primarily concerned with transporting the hand from a starting position to a final location in space. The paths through which the arm and fingers move have to be determined over time. This can be done under the direct control of an active controller, or it can be done in a passive sense. Involved in this latter idea is the notion that the controller sets up key parameters, and lets the 'physics acting on the system' do the control. Task planning, on the other hand, is used to achieve some goal. A task plan consists of desired subgoals without regard to the details of the actions necessary to accomplish them.

Since these two types of planning are fundamentally different, task planning is addressed in this chapter, and trajectory planning and movement execution are detailed in the next chapter.

4.2 Task Plans

A task plan is a scheme for achieving a goal. A goal to grasp a hammer in order to place it on a shelf must be broken down into a method for achieving that goal. In this section, task plans and their components are evaluated at three different levels: as a plan one might construct for a robot, as a plan distributed over many processes, and as a plan as it might look in the nervous system.

4.2.1 Robot task plans

In the robotics literature, task plans are constructed in order to achieve some goal (see Figure 4.1). For example, Lozano-Peréz and Winston (1977) list five phases involved in a task such as 'insert peg in hole'. First, there is a gross motion to get the arm to the peg. Once this is achieved, the gripper opens and grasps the peg. There is then a gross motion to move the arm to the hole while the hand is holding the peg. Then there is a fine motion of the arm during the time the peg is being pushed into the hole, while the controller complies with the forces generated by such activity. Finally, an ungrasp occurs where the hand opens, thus releasing the peg. Using the language, LAMA, Lozano-Perėz and Winston construct these steps as a task plan containing five commands. However, this represents only a general scheme for what to accomplish. In order to actually perform the task, this 'skeleton' plan is filled out by LAMA. Extra commands are added describing the sensory information necessary for performing the sub-task. For example, the fine motion command is expanded into the following guarded motion commands:

MOVE ALONG Z-AXIS
STOP WHEN FORCE ALONG Z-AXIS = 100 NEWTONS

This specifies both the direction of the movement in the hand's Cartesian coordinate frame and also the force sensor to test for sub-task completion. As specified, there is still no guarantee that the peg will be inserted in the hole, for example, if the gross motion moves to an incorrect location and the hand is now pressing against the table surface.

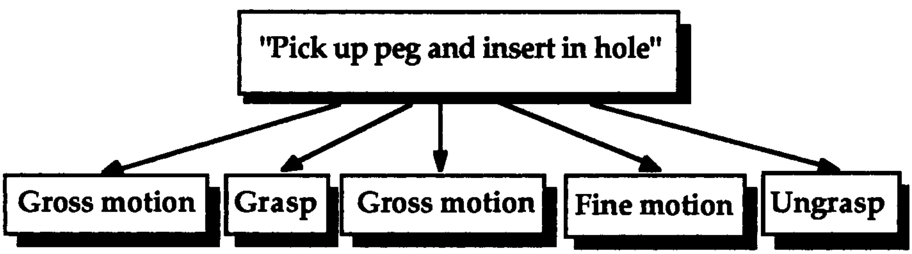

Figure 4.1 Task plan for robot manipulator and end-effector. Lozano-Perėz & Winston (1977) identify five phases for this task. In LAMA, a task plan is a skeleton version of a plan that is filled in for a feedback controller.

What can be observed about this task plan? The goal of 'insert peg in hole' is subdivided into sub-tasks occurring in serial order[1]. As in

[1]In an analagous framework within the human movement literature, Lashley (1951) was concerned with the representation of serial behaviour in order to achieve a goal.

our hammer example, before the hammer is placed on the shelf, it must be picked up; before it is grasped, the hand must first open up. Successive movements are affected by earlier movements in a sequence. As well, earlier movements show anticipatory planning for subsequent ones. There is no guarantee that each sub-task controller will be able to complete its sub-task, and thus this plan is open-loop. The sequence of events is predetermined and applied regardless of errors. At the same time, the details of what is occurring within each sub-task controller are not relevant to the overall plan. In fact, the task planner constructed the plan as a skeleton of calls to sub-task controllers. Each sub-task controller gets filled in and performs its piece of the work towards achieving the overall goal. Details about the frame of reference, the type of movement, and the type of control to use are expanded upon and then performed. As we saw in the fine motion example, a sub-task controller is constructed that uses sensory feedback to perform a guarded motion because contact with the environment is occurring.

4.2.2 Distributed processing task plans

The Arbib (1985) coordinated control program (CCP, see Figure 3.3) is a task plan using schemas for sub-task controllers. Just as in the LAMA example, each schema in the plan is involved in some aspect of the overall task. However, the LAMA plan was written on a computer in a modular, but serial format. The CCP is a parallel distributed processing model for how the CNS might function. For a given task, all motor schemas in the model are instantiated at the same time and control lines (dashed lines in Figure 3.3) are activated. When critical data are received or some processing has occurred, the schema starts performing its sub-task. Thus, serial order in a CCP is achieved by the use of activation signals and the passing of control parameters and data from perceptual to motor schemas[2]. Order is specified without a central representation. The actual working of each motor schema, again as in LAMA, is at another level of detail and can be modelled depending on what is known about control in the CNS.

For a task of hitting a nail with a hammer, not only must the hammer be grasped correctly for the task, it must also be brought to bear squarely against the head of the nail. Is error handling part of the

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[2]Schema programming has been done in the robot schema language **RS** (Lyons and Arbib, 1989). **RS** formalizes schemas as port autamata that can be instantiated and deinstantiated.

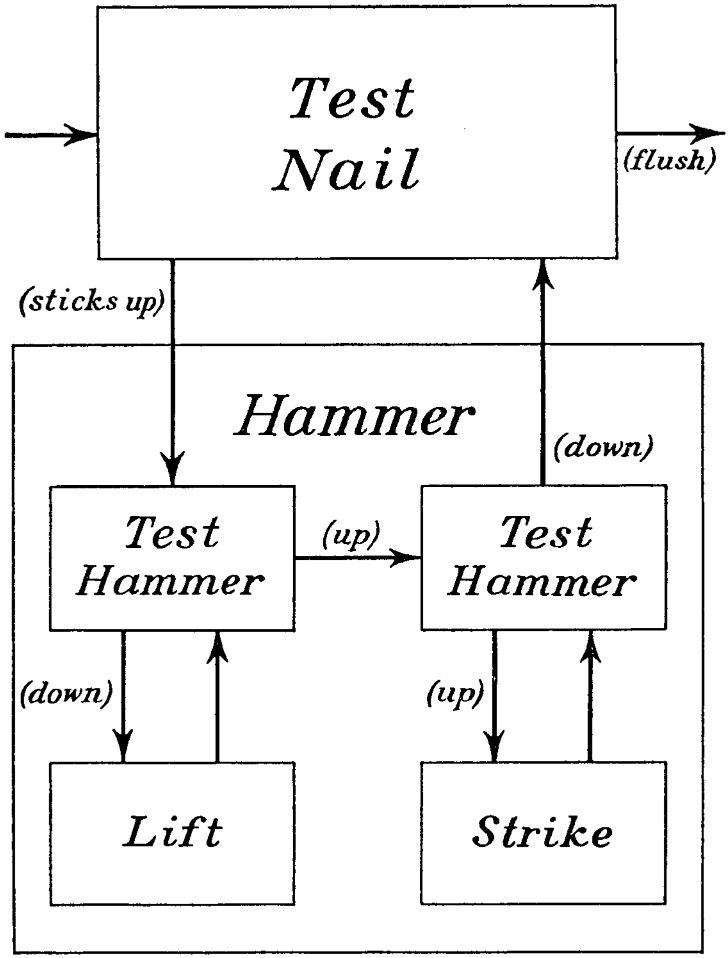

Figure 4.2 The TOTE (Test-Operate-Test-Exit) mechanism operates to determine successful completion of hammering the nail. TOTES deal with the correction of errors and ensure successful completion of one level of analysis of the task (from Miller, Galanter and Pribram, 1960; reprinted by permission).

plan, and if so, how is it incorporated? Arbib would argue that errors are just passed along, and a perceptual schema would note a mismatch between the current scene and anticipated scene and would therefore reprogram the motor task. One way to achieve this is to represent the goal in terms of sensory consequences[3], an argument made by Schmidt (1975) and Cole and Abbs (1987). Then, mismatches between the actual outcome and the anticipated sensory consequences would cause reprogramming. But the error processing can also be incorporated into the plan, as modelled with TOTES (Miller, Galanter & Pribram, 1960). A TOTE (Test-Operate-Test-Exit) is a hierarchically organized processing model, as seen in Figure 4.2. In order to hammer a nail, if the hammer is up, the hand will bring it down; if down, the hand will bring it up. The 'Test-Nail and Hammer' TOTE hierarchically calls the 'Test-Hammer and Lift' TOTE and the 'Test-Hammer and Strike' TOTE. These, in turn, would call other, lower-level TOTES as necessary. The actual representation of the goal state for each test box could be in terms of sensory consequences (or perhaps in terms of the sensorimotor contingencies seen by a feedback controller). In the Arbib CCP, motor schemas could be performed by TOTES.

One reason to hide the details of the schemas is that numerous spatial-temporal patterns of action can produce the same results. This fact of movement behavior, called motor equivalence, has to do with the nonspecificity of motor commands. Muscles can vary their functional roles from movement to movement. As well, there is a great deal of variability in movements, because two similar movements are never exactly alike. However, these variations occur within a restricted bandwidth. A hierarchical model (recall the ballpark model of Greene, 1972) built from a high level plan that approximates a movement goal and then is refined at lower levels explains movement anomalies such as motor equivalence and variability. In terms of motor equivalence, lower level subsystems are interchangeable. In terms of variability, a plan is implemented through one to many transitions. A hierarchical system reduces control complexity.

Motor equivalence and variability in repeated grasping instances raise a question about the components that make up a plan: if there is more than one way to perform something, what is invariant in the plan? In the Arbib CCP, there is a distinction between the motion of the arm (left side of Figure 3.3) and the motion of the hand and wrist

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[3]Sensory consequences are distinct from the sensory motor contingencies required during movement execution. Unfolding of the program for movement includes descending commands, and also contingencies for sensory information in anticipatory feedforward control. This would allow for adjustments to unexpected perturbations or the requirements of subsequent phases. An example of this will be seen in Chapter 5.

(right side of Figure 3.3). The details, as well as the variations that might occur with each grasping instance, are present within each schema. The only invariances suggested in Arbib's model are the triggering of the schemas.

4.2.3 Neural task plans

In a typical experiment to study movement latencies, Jeannerod and Biguer (1982) had subjects move as "fast and accurate" as possible to reach and grasp an object placed in a specific location, in response to a visual go signal. They measured arm and hand muscle activation as subjects reached for and grasped an object. Recording the activity level of electromyography (EMG) data, Jeannerod and Biguer noted a 250 ms lag time from the 'GO' signal to a burst in EMG activity in the biceps muscle of the arm (see Appendix A). About 20 ms later, an EMG burst was seen in the extensor digitorum communis, the muscle used to extend the fingers as the hand opened from the initial resting posture of thumb and index finger pads touching. Actual movement of the fingers occurred about 80 to 100 ms later, which is the electromechanical delay time for isometric tension to be established in the muscle.

While Jeannerod and Biguer noted a 250 ms lag time, the time lag that it takes for the subject to initiate movement is not fixed. This time to react after a stimulus, or reaction time, can vary depending on a myriad of factors including the difficulty of the task. More complex tasks generally increase the reaction time of the subject. For simple movements, the reaction time is shorter than for more complex movements. For example, in a classic study done by Henry and Rogers (1960), subjects were asked, in response to an auditory "go" signal, to make either a simple movement (lift finger from key), a complex movement (lift finger, reach and grasp suspended ball), or a more complex movement (lift finger, reach forward and strike suspended ball with back of hand, reverse direction to push button, and then strike another suspended ball). For adult subjects, mean reaction time increased as the movement complexity increased, from 158 ms for the simple finger lift task to 197 ms for grasping to 213 ms for the more complex movement sequence requiring ball strikes and changes in direction. More recently, reaction times to initiate grasps have been unaffected by systematic manipulations of object texture (Fikes, Klatzky & Lederman, 1993) or orientation (Stelmach, Castiello & Jeannerod, 1993). Thus time to intiate a grasp depends on the sensory modality for processing the go signal (auditory or visual),

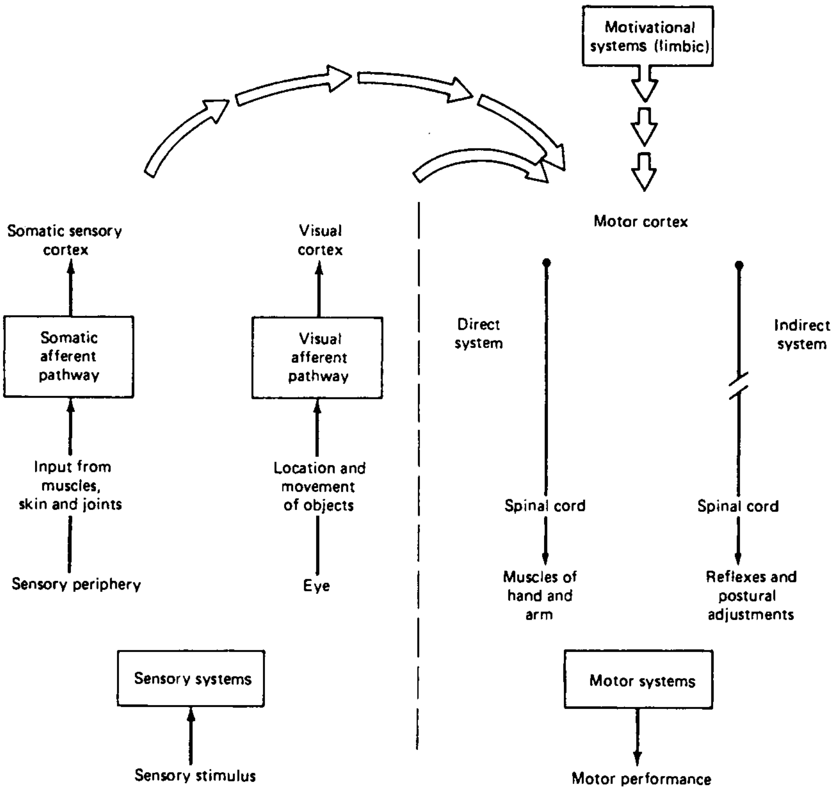

Figure 4.3 Three major brain systems - the motivational systems, the sensory systems and the motor systems must interact during an act like reaching to grasp an object. The motor cortex receives inputs from the motivational systems, and sensory systems. In parallel, descending systems from the cortex include the direct corticospinal system, which makes monosynaptic connections to the motoneurons of the hand muscles, and also connections to the motoneurons of the shoulder and arm muscles. Indirect pathways descend from the motor cortex and multiple brainstem structures to make connections with postural muscles. All of these systems are reflected in the delay between a 'GO' signal, and the first EMG burst observed prior to initiation of the grasping movement (from Kandel and Schwartz, 1985; reprinted by permission).

and the complexity of the upcoming grasping task. To date, no research has shown reaction time to vary with object properties.

What is happening during this time delay? Evidence suggests that the CNS is engaged in preparatory processes related to the organization and planning of the upcoming movement. These processes include activity in motivational systems, sensory systems and motor systems. Figure 4.3 shows how these three systems must be coordinated during the delay interval, to process the 'GO' signal and prepare the effectors. There could be some preparation of spinal networks prior to and immediately after receipt of the visual signal to go; that is, this model of the brain systems need not be a strictly serial processing model whereby the stimulus must be processed prior to any motor processing.

It is noteworthy that the motivational systems are viewed traditionally to act through two separate, independent motor systems, the somatic motor system and the autonomic nervous system (Kandel & Schwartz, 1985). In the planning and control of hand movements, attention had been directed almost exclusively to the somatic nervous system; however, the sympathetic nervous system prepares the body for action, from innervation of the ciliary muscles of the lens of the eye to the eccrine sweat glands of the hand (discussed in Chapter 6).

Although the CNS consists of billions of individual nerve cells, decades of neuroscience research have shown that they combine into regions, some of which are shown in Figure 4.4. Kalaska and Crammond (1992) summarize much of the research, suggesting that each area is concerned with motor planning at a different level of abstraction. Sensory information from the skin and muscles can act at multiple levels: within the spinal cord, at the same or other segmental levels; acscending through the spinal cord and brainstem with synaptic relays in the dorsal column nuclei and the thalamus; and in the somatosensory and motor areas of the cerebral cortex. Brainstem and subcortical regions (e.g., basal ganglia, red nucleus, cerebellum) are distinguished from regions in the cerebral cortex, the large hemispheres that fill up most of the cranial cavity. In the frontal lobe of cerebral cortex, motor areas have been distinguished, including the primary motor cortex (M1, or Brodmann's Area 4), supplementary motor cortex (MII, or SMA), and premotor cortex (PM, or Area 6). In the parietal lobe behind the central sulcus, are found primary somatosensory cortex (SI, or Areas 3a, 3b, 1 and 2), secondary somatosensory cortex (SII), and posterior parietal areas (Area 5 and 7).

One way to determine the functionality of CNS preparatory processes is by recording electrical potentials at the surface of the brain. It has been noted that different localized areas are active during this period prior to movement. For example, Deecke, Heise, Kornhuber, Lang, and Lang (1984) observed changes in potentials beginning about 800 ms before onset of movement in rapid finger or hand

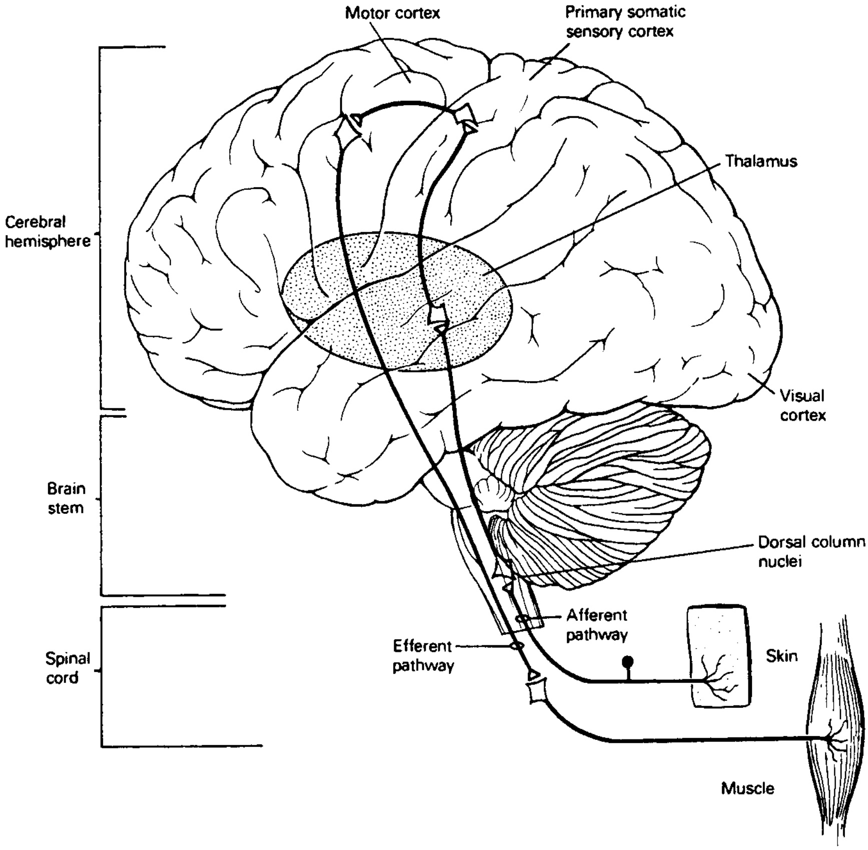

Figure 4.4 Levels of the CNS include the cerebral hemispheres, brain stem and spinal cord. Sensory and motor systems innervating the trunk and limbs must cooperate and integrate information in order to carry out a behavioral act such as grasping an object. Afferent information acts at spinal levels or ascends, synapsing in the dorsal column nuclei and thalamus before reaching the somatosensory and motor regions of the cerebral cortex. The direct motor pathway descends from the motor cortex to excite motoneurons in the spinal cord, monosynaptically or through interneurons. The excitability of these motor neurons is also a function of spinal and descending influences from rubrospinal, reticulospinal, tectospinal and vestibulospinal pathways (from Kandel and Schwartz, 1985; reprinted by permission).

movements, with a pre-motion positivity above the precentral motor cortex occurring at about 90 ms before detectable EMG activity in the forearm. While this 80-100 ms discharge in motor cortex prior to the motor response has been firmly established, the contributions of other regions is not as clear. In cortical and cerebellar studies in awake performing primates, Lamarre and Chapman (1986) were able to determine relative timing by recording neuronal activity from various parietal and frontal areas and the cerebellum. They found parietal regions initially respond to the stimulus about 180 ms prior to movement, followed by responses in the lateral cerebellum 160-100 ms prior, and then motor cortical responses about 85 ms prior to movement onset.

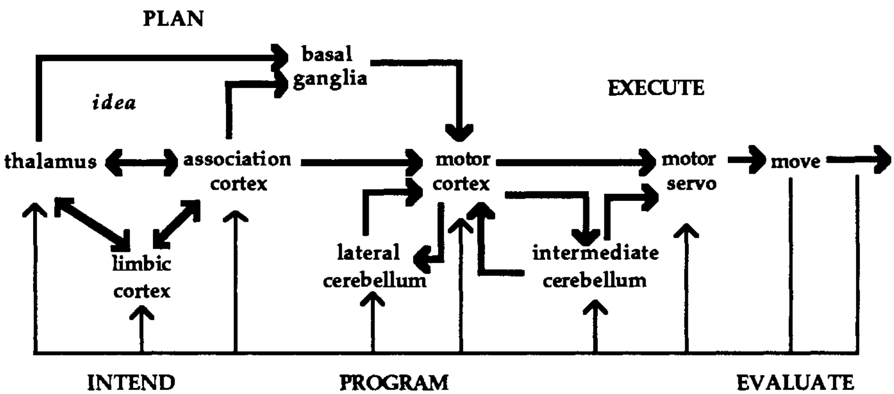

Figure 4.5 Structures of the CNS involved in planning, programming and execution of prehension movements (from Paillard, 1982a; adapted by permission).

An intriguing model of how cortical and subcortical areas might be involved in the planning and execution of movements was developed by Allen and Tsukahara (1974) and extended by Paillard (1982a). As seen in Figure 4.5, the regions of the cerebral cortex, basal ganglia and cerebellum are all involved in the planning and program parameterization prior to movement initiation. Planning evolves within the association cortex, the limbic cortex, lateral cerebellum and basal ganglia, all of which send motor commands to the motor cortex. The motor cortex, in turn, programs lower centers for the execution of the movement (trajectory planning). Sensory information from the periphery is fed back to cortical areas for further planning and commands.

As a simplified view of the CNS, it is a useful model for localizing some of the functions that task plans must perform. Motivations, emerging from limbic structures, are converted to goal-directed, serially-ordered movements, using cortical and subcortical mechanisms. Cortical areas include the parietal association cortex, involved in the precise visual guidance of goal-directed arm and hand movements, and the frontal association cortex, involved in the processing of perceptual cues and memory stores. Subcortically, the basal ganglia, converging on secondary motor areas (SMA and dorsomedial area 6), are involved in strategy selection in accordance with goals and the context for the actions. The role of motor cortex is more part of movement execution, that of advanced tactile and proprioceptive adjustment of the fingers and hand.

One way to study planning at the CNS level is to delay the signal to initiate the movement. In monkey studies where the direction of intended movement is given, but the GO signal is delayed (Wise, 1985), neurons in the dorsal premotor area show directionally tuned activity during the delay period. Hocherman and Wise (1991) find that these responses vary with both target location and degree and intended curvature of the hand path.

Research has shown that CNS processing is different when processing object property information for object recognition and naming, compared to manual interactions with the object. For example, after processing by the visual cortex, the parietal lobes are involved more extensively in visuomotor processing for reaching and grasping objects, whereas the temporal lobes are more involved in processing information for object recognition. (Wise & Desimone, 1988; Goodale, Milner, Jakobson & Carey, 1991).

While neural models are a gross simplification of the brain, they are useful for making important observations. The brain consists of billions of neurons, each making thousands of connections on other neurons. Information is processed to convert motivations into motor activity through the help of sensory information. Information, goals, control, and commands are distributed somehow across these arrays of processors. Yet, studies on the primate brain suggest conflicting evidence as to the nature of the information: there can be body-space or world-space reference frames, the language can be kinematic or dynamic, control can be feedforward or feedback, and commands can be at the movement or muscle level. There is likely a separation of neural computation for planning (frontal and parietal association areas, and basal ganglia) from execution (motor cortex and cerebellum).

With this in mind, we turn to study the processing that is necessary for the planning of prehensile behaviors.

4.3 Perceiving Object Properties

Intrinsic object properties are the physical identity constituents of objects, such as size, weight and shape. Extrinsic object properties are spatial properties of objects in an egocentric body space, such as distance, orientation with respect to the body, and, if in motion, direction and velocity of the object. In this section, visual information during the planning of prehension is discussed.

4.3.1 Perceiving intrinsic object properties

Objects have properties that are intrinsic to their design. These can include structural properties, such as shape, size, distribution of mass, and weight, and also surface properties, such as texture, temperature, and hardness. Intrinsic properties affect the selection of a grasp posture, as was observed in the discussion on grasp taxonomies in Chapter 2. For example, the shape and size constrains the type of opposition used, how many fingers can be used and where they can be placed on an object. Intrinsic object properties can be perceived primarily through vision or haptics. During the planning phase, only visually perceived object properties are available. After contact with the object, object properties can be perceived haptically, and this is addressed in Chapter 6.

Some intrinsic object properties in particular are accessible to the vision system. Klatzky and Lederman (Klatzky & Lederman, 1987; Klatzy, Lederman, & Reed 1987; Lederman & Klatzky, 1987) have determined that spatial density (a surface property and aspect of texture), volume (or size), and shape (both global and exact shape) are accessible to the visual system. From this, assumptions about other object characteristics are made as well. For example, weight tends to covary with size (large objects tend to be heavier).

Research has shown that humans can judge object size; i.e., they can relate visually perceived object size to how wide the fingers must be open in order to grasp the object. Jeannerod and Decety (1990) asked six subjects to separate their index finger and thumb to an aperture that matched the diameter of a seen target object, ranging in size from 1.4 to 8.4 cm. Subjects could not see their own hand. The tips of the thumb and finger were videotaped and the grip size measured while the posture was maintained for a few seconds. In this pad opposition task, mean grip size correlated positively with object size. Error in matching was computed for each subject as the difference between the grip size used during normal grasping and the person's measured grip size. While object size estimation was shown to be linearly related to the actual object size, errors ranged between ±1.5 cm with very little consistency (of the six subjects, two subjects always underestimated while the rest tended to overestimated). This experiment demonstrates the ability of the CNS to plan an opposition space, but with qualifications. The visual perception of object properties is an estimation (visual scaling) which is shown to be highly accurate. Transforming this visual information into motor commands (visuomotor scaling) causes errors, which Jeannerod and Decety argue could stem from the change from one coordinate system to another. Visual objects are encoded in retinal coordinates, whereas hand configurations are encoded in some other frame. Retinal cues related to object size are not sufficient for determining grip size, particularly in a precision task using pad opposition. They suggest that for accuracy, visual feedback is needed to improve the planned hand posture for correcting visuomotor biases and reducing motor variability.

In a similar experiment, Chan, Carello, and Turvey (1990) asked subjects to use their other hand to evaluate the size of the object. An object was placed in front of the subject, who then used the thumb and index finger of the left hand to indicate the size of the object. Subjects were able to do this accurately in a linear fashion for objects below a 10 cm width. Above that, there were non-linearities due to a ceiling effect; that is, there were biomechanical constraints on the hand. Using the thumb and middle finger removed these non-linearities.

The speed with which object properties are perceived is important. Klatzky et al. (1987, 1990) analyzed the two-dimensional perception of objects, arguing that the projection of a three dimensional object on the retina can be used for making decisions about interacting with the object. By varying the area and depth of the two-dimensional projection of an object, they showed an effect on the chosen grasp. As seen in Figure 4.6, subjects pinched small things and clenched larger things. Since object size is a critical planning parameter, it is noteworthy that a simple two-dimensional representation of the object can be used for choosing a grasp posture. This representation is available at the level of the retina, thus quickly accessible to the CNS.

Intrinsic object properties can be perturbed at movement onset in order to observe how long it takes to perceive object properties, or at

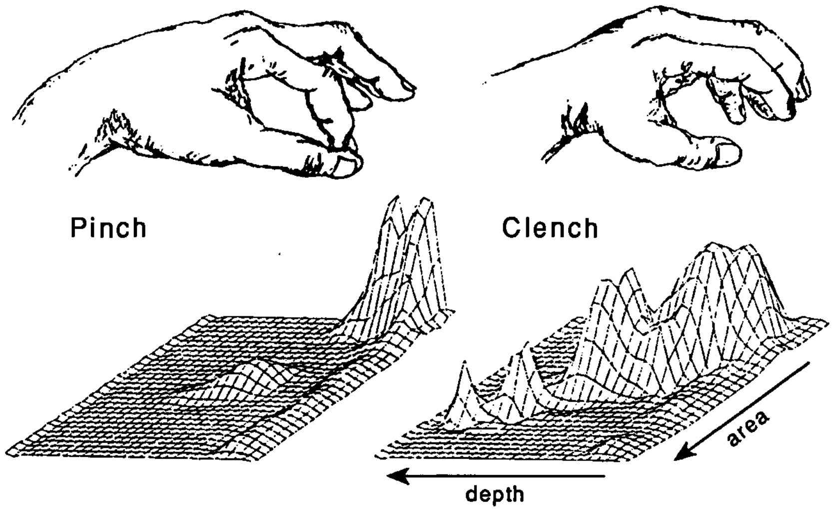

Figure 4.6 Interpolated spaces for pinching vs clenching a two dimensional object. Pinch is shown on the left and clench on the right. The percentage of subjects naming a given hand shape in response to an object cue is shown on the z axis as a function of the object's depth and picture-plane area (from Klatzky, et al., 1987; adapted by permission).

least to effect movement changes based on changes in the object property. By observing the time it takes subjects to make adjustments in the hand posture, one is provided with some clues into CNS prehensile planning. Using a box with a mirror in it and lights strategically placed, Jeannerod (1981) asked subjects to reach out and grasp an object. Initially, the subjects see a spherical shaped object; but as soon as they start moving their hand, an image of an oval-shaped object is superimposed on the sphere. In reviewing the video of the hand as it preshaped for the sphere, Jeannerod noted that it took about 500 ms after the perturbation for the hand posture to change and reflect the more oval-shaped object. No EMG studies were done, but separating out the isometric tension time for the extensor digitorum communis of about 100 ms, this would leave about 400 ms for the subject to visually observe the change, replan a new posture, and generate the new motor commands. Other studies, detailed in Chapter 5 indicate a minimum time of at least 300 ms to effect changes in response to perturbations of intrinsic object properties (e.g., Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991).

In summary, object size is veridically assessed and finely calibrated by the CNS for prehension. Some object properties are accessible more through vision than haptics. Due to the covarying nature of object properties and our previous experience, we make assumptions about object properties like weight, given observations about size. With visual perturbations, replanning for intrinsic object properties in prehension takes at least 300 ms.

4.3.2 Perceiving extrinsic object properties

Studying the nature of extrinsic object property perception can also be done using perturbation studies. Paulignan, MacKenzie, Marteniuk & Jeannerod (1991) performed an experiment where the object's location was perturbed. Subjects were asked to grasp a vertically standing dowel between their thumb and index finger pad. Made of translucent material, the dowel was made visible by means of illuminating a light-emitting diode (LED) placed under the dowel. In this way, Paulignan and colleagues could change the illuminated light, making it appear as if the dowel moved from one location to another. In comparing perturbed trials to control trials, they found that wrist trajectories were modified about 250-290 ms after the perturbation, and the first acceleration and velocity peaks occurred earlier in the perturbed trials. The first detectable difference in wrist trajectories was seen at 100 ms, because the time to the first peak acceleration for control trials was about 130 ms, but for the perturbed ones it was closer to 100 ms. This seems to correspond to the minimum delay needed for sensory reafferents to affect ongoing movement[4]. Corrections might occur by directly comparing target position and limb position signals. Finally, they showed that perturbing the object location influenced the grasping component as well as the transport component. In showing the dissociation of transport and grasping components, because the transport component was completed and the grip size was readjusted, there may be different time constants for the two components. These results are discussed further in Chapter 5.

The orientation of the object is also an extrinsic object property. Jeannerod and Decety (1990) studied the accuracy of matching hand orientations to visually presented object orientations. Subjects held a plate between their thumb and palmar finger surfaces and were asked to rotate the hand to match the seen orientation of the target bar.

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[4]For proprioceptive processing, minimum delay is estimated at 70 to 100 msec (Johansson & Westling, 1987).

Again, they could not see their own hand. Subjects were relatively inaccurate in reproducing orientation. Mean angular errors ranged from 3 degrees to 5 degrees, and a systematic bias was observed in the counterclockwise direction. The relative inaccuracy of matching orientations can be contrasted with the accuracy with which subjects matched object size.

In summary, replanning for extrinsic properties like object location takes about 100 ms; this is a much shorter time than the 300 ms required for replanning grasping based on visual perturbations of intrinsic object properties like size and shape. Further, visually matching seen object orientations with the unseen hand is inaccurate and biased, in contrast with matching seen object diameters.

4.4 Knowledge Of Task Requirements

Over years of practice grasping objects, humans develop a wealth of knowledge about object function and behavior and this knowledge can be used to anticipate and predict the results of interactions. In Chapter 2, we saw that opposition types are a function of both the object characteristics and the task requirements. In the absence of a specific tool (e.g., a hammer) one may substitute another object (e.g., shoe) with a grasp appropriate for the task at hand, given object properties. In contrast, with functional fixedness, one is unable to see other uses of an object designed for a specific function.

Knowledge about the behavior of an object was seen in Figure 2.6. When asked to grasp a mug by its handle, subjects anticipated a torque acting on the mug caused by the posture not being placed around the center of mass. Virtual finger 3 was placed in such a way to counteract this torque. The reason this occurs in the first place is task-related. While the mug can be grasped in a variety of places, grasping it by the handle makes the lip of the mug accessible to the mouth, while protecting the hand from possibly being scalded by a hot liquid. Thus, planning involves knowledge of task requirements, estimation of object properties relative to the task (such as center of mass), and anticipation of object behavior during the interaction.

As well, humans have implicit knowledge of task mechanics. For example, to grasp a square block using pad opposition, one finger can approach the block and push it into the other finger (Mason, 1985). Finger trajectories could be chosen so that a frictional sliding force will orient and center the block in the fingers. The alternative would be to push the block out of the grasp. Knowledge about <u>task mechanics</u> is advantageous in unstructured unpredictable environments, since it eliminates uncertainty without the use of sensors. Mason calls operations that eliminate uncertainty funnels, and argues that manipulation funnels can be used in grasping objects because they eliminate position uncertainty. The use of a manipulation funnel is seen in the way humans let a resting pencil rotate into their grasp by sweeping it up with their fingers.

Is it possible to combine perceived object properties and task information into a summary representation that the CNS might have access to during planning? In Figure 4.7, a process is suggested. For regularly shaped objects (such as cylinders, blocks and spheres) with an equal distribution of mass, the specific location on the object to grasp is not as important as the fact that two (in general) locations are chosen that are generally parallel to each other so that an opposition between two virtual fingers can be applied. We call those two surfaces the opposable surfaces. If they are not parallel, then due to task mechanics, the object will be either pushed into or away from the grasp (see Chapter 6). The surfaces have visible characteristics, such as length, spatial density, and a radius of curvature, all available to the CNS during the planning process. Klatzky, Lederman, and Reed (1987) showed that surface spatial density (an aspect of texture) is an characteristic accessible by vision, as is size. Surface texture relates to the forces needed (rough surfaces are easier to get a grip on). Cutkosky and Newell (Cutkosky, 1989 Cutkosky and Howe 1990; Newell, Scully, Tenenbaum & Hardiman, 1989) demonstrated that size is thought about in terms relative to the hand. The critical hand planning parameters about object size are the object width (how wide does my hand have to open?) and the object length (how many fingers can I use in VF2?). An opposition vector can be drawn between the two surfaces with its magnitude being the width of the object between the two surfaces. Jeannerod and Decety (1990) and Chan et al.(1990) demonstrated that object size can be judged in terms of hand opening size, and Marteniuk et al. (1990) showed that the opening of the hand relates to object size. For irregularly shaped objects (such as mugs, flashlights, tools, etc), Klatzky, Lederman, and Reed (1987) have shown that global shape is accessible to the vision system, thus making it possible to plan without specific details being known. Again, knowledge about task mechanics is relevant here, because it provides a mechanism for anticipating the location of the center of mass. Handles are easily perceivable aspects of objects, because they are regularly shaped and in hand-related sizes. As Napier (1980) pointed out, handles lend themselves to a posture relevant to the task (e.g., power tasks need power grasps which need larger dimensions

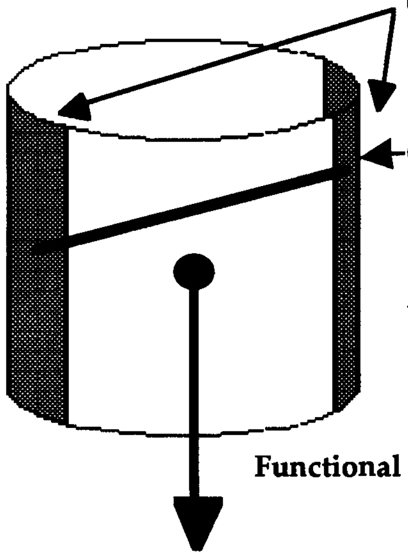

Figure 4.7. An opposition vector is perceived in the object, given task requirements and object properties. The opposition vector has a magnitude, corresponding to the diameter of the cylinder, and an orientation, in an egocentric reference frame. In action-oriented perception, task requirements, intentions and knowledge about task mechanics lead to the percption of task-relevant object properties. The opposition vector perceived would be different if the task required looking inside the glass, compared to precise placement of the glass on a coaster. The opposition vector, seen in the object, is used to select a grasp strategy, and drives the alignment of visual and proprioceptive maps.

than precision grasps).

Just as important as object properties are the task considerations of applying forces and imparting motions. Contributing to the anticipated forces acting on the object are the perceived weight, torques, and inertial forces that will be acting on the object during the interaction. Assumptions are made that weight covaries with size. But it is the center of mass acting at the opposition vector that the hand cares about. Using an opposition vector at the handle of the mug causes a moment with a length the distance from the opposition vector to the center of mass and with a magnitude the weight of the object. For this reason, we tag the task requirements to the opposition vector because this is the relevant frame of reference.

In summary, the CNS seems to store knowledge about how objects behave. This knowledge is accessible to the task plan, and it can only be assumed that it is part of the plan. Planning the precise location for finger placement is not needed, and humans can anticipate object behavior during the interaction between hand and object.

4.5 Selecting a Grasp Strategy

A prehensile posture must be selected that satisfies the object and task requirements. This choice is made based on the human hand capabilities described in Chapter 2, taking into account the precision and power capabilities and specialized features of the hand. The goal is to find a posture that can gather the sensory information, effect a stable grasp and produce motions as needed for the object and given task. The grasp strategy, then, refers to selecting a grasp posture (i.e., selecting oppositions, virtual finger mappings, and hand opening size) and a grasp position and orientation on the object.

4.5.1 Selecting oppositions

One way to make explicit the relationship between object and task requirements and the oppositions needed to satisfy them is to develop a set of mapping rules. This can be done with an expert system which is a computer program that mimics human intelligence by focusing on domain knowledge. In an expert system, knowledge and control structures are separated, unlike more standard programming styles, so that the amassed knowledge of an expert is contained in an easy to analyze, modifiable module. Cutkosky (Cutkosky, 1989; Cutkosky and Howe, 1990) wrote an expert system 'GRASP-Exp' for selecting a grasp posture using observations of one-handed operations by machininists working with metal parts and hand tools. Using the prehensile classification in Figure 2.3, task requirements (forces and motions that must be imparted) and object properties (shape, size, surface geometry) were placed on a continuum and could be used to select a grasp. A set of grasp attributes (sensitivity, precision, dexterity, stability, and security) described the conditions under which each posture can be used. A posture is chosen by GRASP-Exp using a hierarchical analysis of the task, gathering information about the task requirements (e.g., dexterity requirements, clamping requirements) and then the object properties (e.g., thickness, size, shape). To gather this information, GRASP-Exp asks the user questions. In order for the machinists to understand these questions, Cutkosky discovered that they had to be hand-related (e.g., Is the object smaller than your fist?) and analagous task-related (e.g., Is the task like a prying task?).

While asking the user questions, GRASP-Exp looks for supporting evidence that a particular grasp will satisfy the given requirements. It does this using a rule-base, the collection of rules that map task requirements, object properties, and grasp attributes to postures. This method of looking for supporting evidence is called <u>backward chaining</u>. Examples of rules are as follows:

RULE 1:	IF	the task requires dexterity > 75%
	AND	the task requires sensitivity> 75%
	THEN	the grasp is a "precision grasp"
RULE 2:	IF	the grasp is a "precision grasp"
	AND	the object-size is not small
	AND	the object-global-shape is compact
	THEN	the grasp is a "precision circular grasp"
RULE 3:	IF	the grasp is a "precision circular grasp"
	AND	the object-shape is spherical
	THEN	the grasp is a "precision sphere circular grasp"

If GRASP-Exp was in the process of determining whether the grasp is a "precision sphere circular grasp" (Grasp 13 in Figure 2.3), RULE 3 would be used to search for supporting evidence. The controller would search in a backward chaining style, looking for true values for the rule's antecedents or else looking for rules that can be used to determine their true value. In this case, RULE 2 would be triggered because it could be used to prove that the grasp is a "precision circular grasp". However, for RULE 2 to be true, the grasp must first be a "precision grasp". This triggers RULE 1, using backward chaining. But there is no rule that has RULE 1's antecedal data as a consequent, and so the controller would ask the user "WHAT IS THE DEXTERITY REQUIREMENT?" If the dexterity requirement is less than or equal to 75%, this line (whether the grasp is a "precision sphere circular grasp") is abandoned, and another posture selected as the hypothesized answer. As might be seen, the advantage of using backward chaining is that it creates a set of highly directed questions

The advantage of an expert system approach is that it is useful in testing a framework, making explicit the mapping from inputs (object and task requirements) to outputs (hand posture). Such an explicit

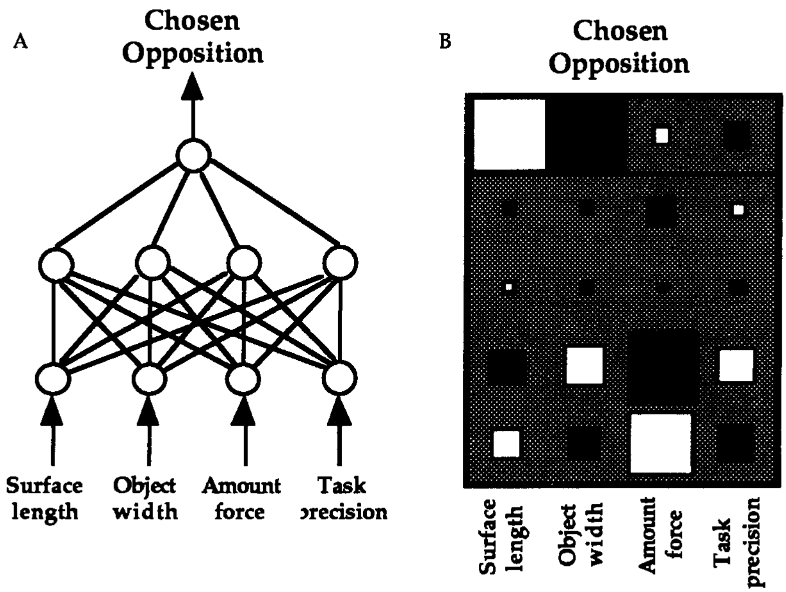

Figure 4.8 Choosing an opposition space from task and object properties using neural networks. A. Network architecture showing four input units, four hidden units, and one output unit. B. Weights between network elements. Black squares are negative weights, white squares are positive weights. The size of the square is proportional to the magnitude of the weight. Grey is threshold. The leftmost column shows weights from the surface length input to the hidden layer, etc. The topmost row represents the weights from the hidden layer to the output unit (from Iberall, 1988).

mapping forces the modeller to be more careful about defining terms, and makes explicit just what the information is that is required in order to deduce the appropriate grasp. In addition, 'what-if' questions can be asked, and patterns or sequences among grasps can be explored.

An alternative approach for choosing oppositions is to use a neural network (See Appendix C for a more detailed explanation of artificial neural networks). In contrast to expert systems, the inputs (object and task requirements) and outputs (oppositions) are characterized but the network learns the mapping rules without their being made explicit. Iberall (1988) used a simulated neural network to chose an opposition for a given set of task requirements. As seen on the left of Figure 4.8, salient task features included two perceived intrinsic object properties (surface length and object width) and two task properties (magnitude of anticipated forces and precision needed). The network computed which opposition should be used (either pad or palm opposition), given the object and task properties. Simply stated, the neural network learned how to choose between palm and pad oppositions given the object characteristics of length and width and the task requirements for force and precision.

An adaptive multilayered network of simulated neurons was constructed for doing this computation (see Figure 4.8a). The network consisted of four input units (bottom row of neurons), four hidden units (middle row) and one output unit (top row). An iterative learning process called supervised learning was used to train the network. A given task (surface length, object width, amount of force, and task precision) was presented to the input layer. An opposition was chosen by summing up weighted activation values of the input units and then weighted activation values on the hidden layer. If any of these weights were set wrong, as they will be initially, the computation will be inaccurate. This computed mapping was then compared to the desired mapping (in the training set). If there was a difference, Iberall used the generalized delta rule to adjust the weights between the input units, hidden layer, and output units in order to reduce this difference.

The training set was drawn from the data points shown in Table 4.1. These were compiled from experimental (Marteniuk et al., 1987) and observational data that pertains to mapping task requirements to grasp postures. Input requirements are stated in terms relative to the hand's size and force capabilities. Object size has been broken down into two separate properties: object length and object width. Length is measured in terms of the number of real fingers that can fit along the surface length at the opposition vector, and width is in terms relative to hand opening size. Task requirements have been broadly and subjectively characterized in terms of power and precision requirements: magnitude of forces (without regard to their direction) and precision needed. Grasp postures are characterized by the chosen opposition. In the case of grasping a beer mug by its body, the surface length is greater than four fingers, the width of the mug is generally large relative to the span of the hand, and the weight of the filled mug is relatively heavy. Lifting it requires a large translation upward, involving little precision. In this task, palm opposition has been observed. For heavy objects, palm opposition tends to be used with as many fingers as possible. As the weight of the object decreases, the posture switches to pad opposition.

For computing the difference between the desired output and the

Table 4.1 Training set for neural network. A task is defined by task requirements, which are stated in terms relative to a hand and its capability. For the given task requirements, either pad or palm opposition is selected (from Iberall, 1988; adapted by permission).

TASK	TASK REQUIREMENTS				CHOSEN
	Surface Length	**Object Width**	**Size of Forces**	**Precision Needed**	**OPPOSITION**
Lift heavy beer mug	> 4 fingers	large	large	low	PALM
Lift long steel cylinder	> 4 fingers	medium	large	low	PALM
Lift short cylinder	3 fingers	medium	large	low	PALM
Place wide short steel cylinder	2 fingers	large	medium	high	PAD
Lift large glass	> 4 fingers	large	medium	medium	PAD
Place cylinder	> 4 fingers	medium	small	high	PAD
Lift small disk	1 finger	small	small	medium	PAD
Lift med. disk	1 finger	medium	small	low	PAD
Place med. disk	1 finger	medium	small	high	PAD
Throw med. disk	1 finger	medium	medium	low	PAD

computed ouput, a logistic activation function was used. A momentum term was added in order to increase the learning rate. An error cutoff of 0.05 was used to indicate that the network learned the training set. It took 833 repetitions of the training data to converge on a solution. The weights into which the network settled are seen in Figure 4.8b. The first row of squares from the bottom represent the weights on the links from the input units to the first hidden neuron (hidden neuron on the left in Figure 4.8a). The size of the square is proportional to the magnitude of the weight. Larger squares mean a larger influence. A negative influence is shown by black squares, positive by white. The second row of squares from the bottom represent the weights to the second hidden neuron, and so on. As can be seen, the size of the squares in the third row from the bottom are close to zero and thus the third hidden unit from the left has little influence on the overall computation. The top row of squares represents the weights coming from the hidden layer to the output layer. The first two hidden units have a large influence, whereas the other two hidden units have a moderate influence.

The point of using a neural network approach is to learn how it generalizes. In analyzing how the network generalized the input/output space, Iberall noted that it learned to use palm opposition when the forces were large. With higher precision requirements in the task, the network choose pad opposition. Also, there was a tendency toward using palm opposition when the length of the object increased, particularly when the forces were increasing as well. These results mirror information observed in human prehension.

Uno et al.(1993) developed a neural network for determining optimal hand shapes. As seen in Figure 4.9, the network had five layers. During the learning phase, the network sampled object shapes and hand postures. During the optimization phase, the network was

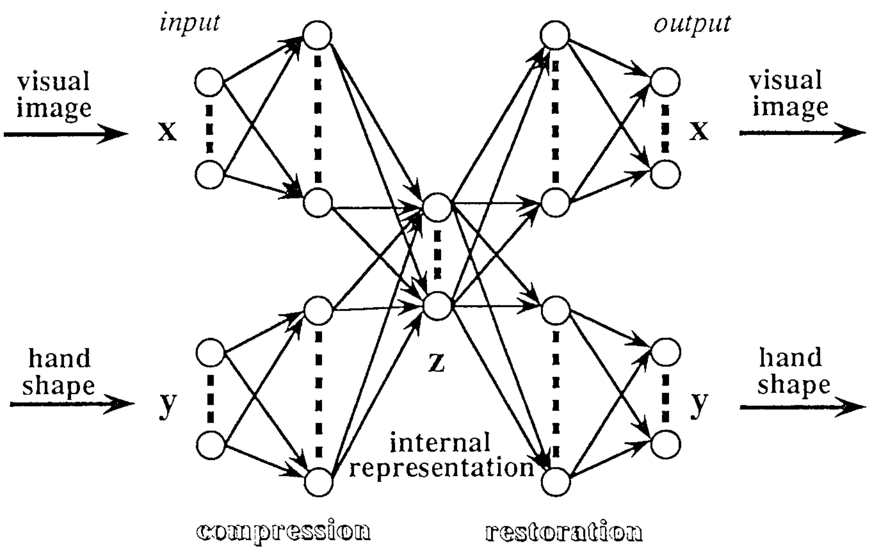

Figure 4.9 Neural network for objects and hand postures. During the learning phase, two dimensional visual images of objects and DataGlove sensory data representing hand postures are presented to the network. During the optimization phase, an optimal posture is chosen based on a criterion function (from Uno et al., 1993; reprinted by permission).

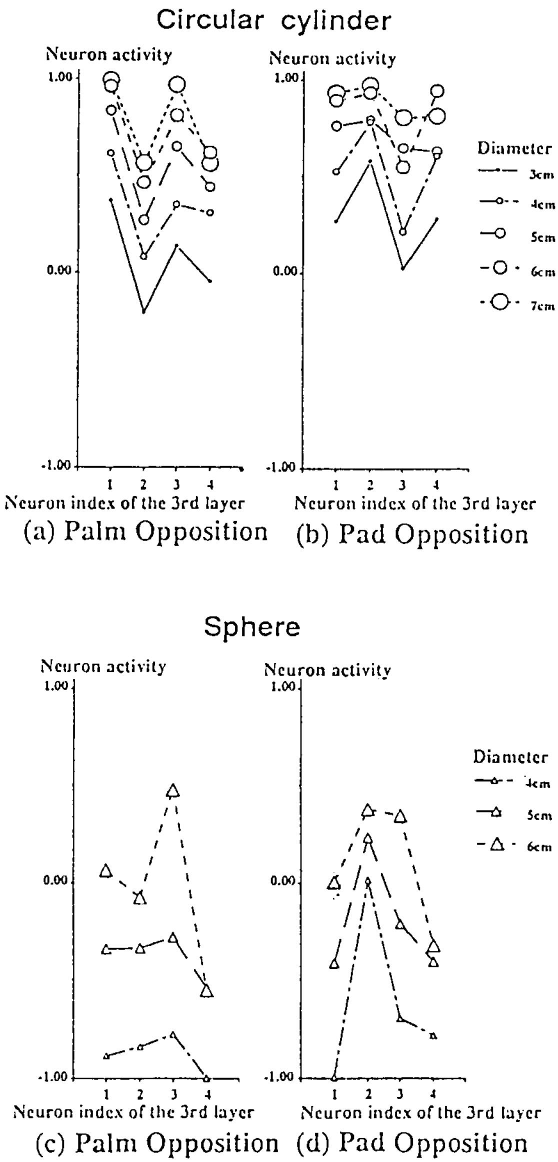

Figure 4.10. Internal representation for grasped objects. a) Grasping different size cylinders in palm opposition. b) Grasping different size cylinders in pad opposition. c) Grasping different size spheres in palm opposition. d) Grasping different size spheres in pad opposition (from Uno et al., 1993; reprinted by permission).

able to generate an optimal hand posture for a given object. The input to the network consisted of two dimensional visual images of different sized and shaped objects. Cylinders, prisms, and spheres were used, varying in size from 3 cm to 7 cm. The other input to the network during the learning phase was prehensile hand shapes, using data collected from a DataGlove (VPL, Inc., California). The DataGlove had sixteen sensors recording thirteen flexor/extensor joint angles and three abduction/adduction angles. Two types of hand postures were used: palm opposition and pad opposition. During the learning phase, objects were grasped repeatedly using a trial and error approach. The network learned the relationships between the objects and postures. As seen in Figure 4.10, the third layer of neurons is examined in order to see the internal representation. The level of neuronal activity increased with object size. The activation patterns for the same objects were similar. In terms of oppositions, the neuronal activation patterns were different for pad vs palm opposition. Choosing the correct hand posture to use based on object properties is an ill-posed problem, since there are many possible solutions. Therefore, during the optimization phase, Uno et al. used a criterion function to make the selection. The function $C(y)=\Sigma y^2i$, where i is the ith output of the sixteen DataGlove sensors, is mimimized when the hand is flexed as much as possible. Using relaxation techniques during the optimization phase, the network minimized this function and computed an optimal hand posture for a given object.

A problem with these models is the limited number of inputs and outputs. The versatile performance of human prehension, in contrast, can be viewed as emerging from a large multi-dimensional constraint space. In Chapter 7, sources of these constraints are identified and grouped together into ten different categories. The list brings in the notion of higher level goals working together with harder constraints.

4.5.2 Choosing virtual finger mappings

An important component to the grasp strategy is the number of real fingers that will be used in a virtual finger. Newell et al. (1989) studied the number of fingers used in opposition to the thumb as adults and children grasped cubic objects ranging in width from .8 to 24.2 cm. For the largest objects, two hands were used; more children than adults used two hands. In general, the number of fingers used in opposition to the thumb increased with object size. As expected, one finger was used with the thumb at very small object sizes, and all four fingers were used in opposition to the thumb for the largest cubes.

For intermediate objects, there were preferred grip patterns of two or three fingers in opposition to the thumb. Further, the frequency curves and patterns of hand use were similar for adults and children when plotted against the object/hand ratio.

Iberall, Preti, and Zemke (1989) asked subjects to place cylinders of various lengths (8 cm in diameter) on a platform using pad opposition. No instructions were given on how many fingers to use in VF2 as it opposed the thumb (VF1). Of the fifteen finger combinations possible, seven combinations were used (index, middle, index & middle, middle & ring, index & middle & ring, middle & ring & little, index & middle & ring & little). The size of VF2 was 1, 2, 3, or 4 fingers wide, although 60% of the grasps used a VF2 of 1 or 2 fingers. It was observed that more fingers were used in VF2 as cylinder length increased, supporting Newell et al. (1989). Surprisingly, of the VF2 with a width of one, subjects tended to use their middle finger (M). In terms of finger occurrence, use of the middle finger (M) was seen almost all the time, particularly since six of the seven postures include the middle finger. Both the index finger (I) and ring finger (R) increased in usage as cylinder length increased. The little finger (L) was brought in for largest cylinder.

How might virtual finger planning be modelled using artificial neural networks? Iberall, Preti, and Zemke (1989) constructed a network to determine a real finger mapping for virtual finger two (VF2) in pad opposition (Figure 4.11). The neural network learned how to assign virtual to real finger mappings given length as the object characteristic and difficulty as the task requirement. Supervised learning was used to train the network. The training set was constructed using data from the experiment described above. Training pairs were presented to the network in thousands of trials until it learned to assign the correct mapping of virtual to real fingers given these inputs.

Using the same supervised learning algorithm as previously described, different tasks (task difficulty, cylinder length) were presented to the input layer. The number of real fingers to use was computed by summing up weighted activation values of the input units and then weighted activation values on the hidden layer. Iberall et al. used the generalized delta rule to change the weights between the input units, hidden layer, and output units. An error cutoff of 0.05 was used to indicate that the network learned the training set, and had converged on a solution.

Different architectures for adaptive neural networks were designed. A network architecture that decides the average number of fingers to use in virtual finger two (not shown), and percentages

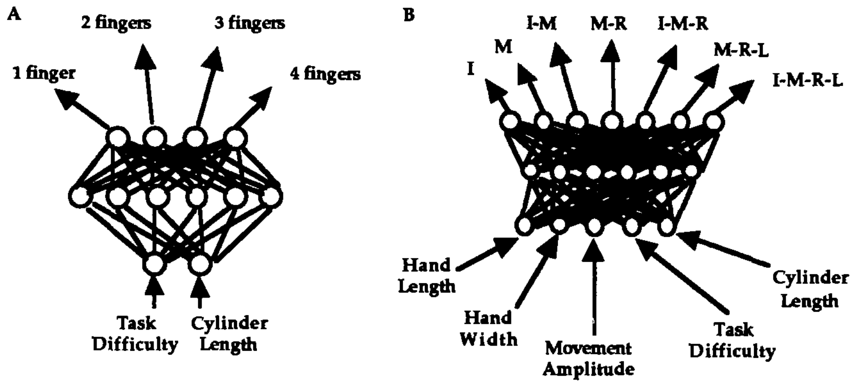

Figure 4.11 Networks modelling virtual to real finger mapping. A. Using task difficulty and cylinder length as inputs, the network computes the size of virtual finger two. B. Using task difficulty, cylinder length, hand length, hand width, and movement amplitude as inputs, the network selects which real fingers constitute virtual finger two. I=index finger, M=middle finger, R=ring finger, L=little finger (from Iberall, Preti, & Zemke, 1989).

across all subjects took 1033 cycles to converge (total error .003). Using a different network (as in Figure 4.11a) with four outputs, each one telling the liklihood of a virtual finger size, took 2072 cycles to converge (total error .004). The training set used percentages across all subjects. A network with seven outputs, one for each combination, and percentages across all subjects, took 3000 cycles to converge (total error .001).

However, the goal is to model one person's brain, not the average brain. When Iberall et al. tried the same network using one subject's data, the network could not compute a solution. This is because subjects used different combinations for each condition. Even though a subject typically used the middle finger in opposition to the thumb, for a few of the trials he or she would use the index in addition to the middle finger, and then revert back to the standard grasp. In order to more closely model the person, more inputs were added, such as features of that individual's anatomy and more about the task, as seen in Figure 4.11b. The network still didn't converge. Likely, more dynamic inputs are needed, such as level of muscle fatigue.

Adaptive artificial neural networks can be trained using data from experimental evidence, and then tested on other data. Converging on a solution means that a solution has to exist. However, this depends

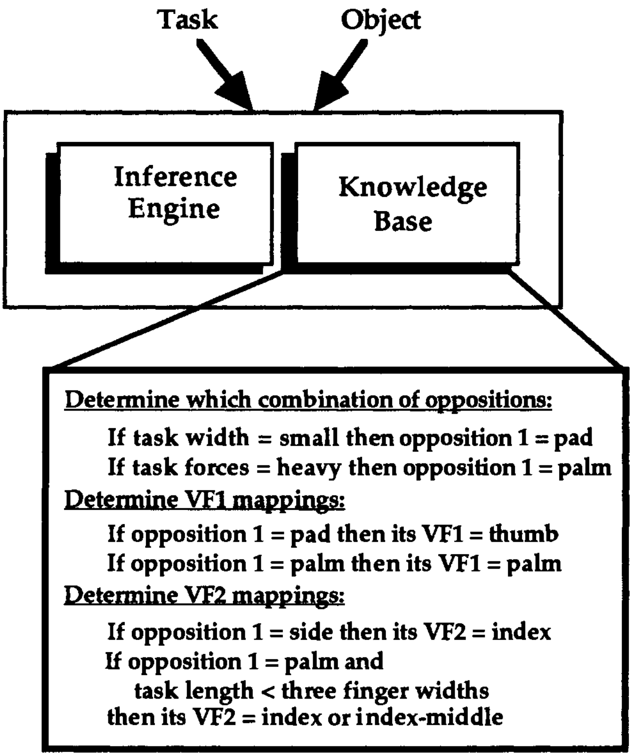

Figure 4.12 Sample rules in knowledge-based system for selecting an opposition space from object and task requirements. Three types of rules are used. First, oppositions are chosen. Then, for each opposition, the mappings from real fingers to virtual fingers are made. Task width refers to the length of the opposition vector. Task length refers to the height of the object. VF=virtual finger (from Iberall et al., 1988).

on the number of constraints being modelled in the system. Again, the human brain controlling the hand is working with a large multidimensional constraint space, as outlined in Chapter 8.

An expert system can combine choosing oppositions and virtual finger mappings (Iberall, 1987c; Iberall, Jackson, Labbe & Zampano, 1988). As seen in Figure 4.12, the system had three types of rules. Similar to the GRASP-Exp rules, the first set of rules in this system chose which oppositions were needed depending on object properties (size, weight, surface characteristics) and task properties (anticipated forces, precision requirements). The second set was used to determine the mapping for VF1 for each chosen opposition. As a simplifying assumption, this was fixed (i.e., the palm is VF1 in palm opposition, the thumb is VF1 in pad and side oppositions). The third set determined the mappings for VF2. This depended both on the type of opposition and on object and task characteristics. For example, VF2 could not be wider than the length of the object at the grasp site location.

The advantage to such an encoding of postures is that it provides a set of parameters that are potentially being controlled in human prehension. Further, these parameters can be quantified experimentally, used in computational models and implemented in artificial hands.

4.5.3 Selecting hand opening

We discussed earlier that humans are quite accurate at matching the distance between two opposable surfaces of an object with an aperture between the thumb and index finger, whether the two opposable surfaces are assessed visually (Jeannerod and Decety, 1990) or haptically, by holding the object in the other hand (Chan, Carello, and Turvey, 1990). These experiments demonstrate that the CNS can plan a hand opening to match a perceived object. Further, in the context of reaching and grasping, Marteniuk et al. (1990) found that peak aperture increased by 0.77 cm for every 1 cm increase in the diameter of the cylinders, with a correlation of .99. Aperture evolution is continuous, and reveals that even at onset of hand opening, aperture size increases with object size. Thus experimental evidence suggests that the hand opening appropriate for the magnitude of the opposition vector is selected prior to movement onset.

4.6 Planning a Hand Location and Orientation

Once the object's location and orientation are perceived, arm movements can be planned that will put the hand into a suitable location and orientation. One way to view planning is the process of transforming information from a visual reference frame to arm muscle activity. Computations such as transforming a desired goal into motor commands lend themselves to modelling with artificial neural network models of CNS activity, as is seen in this section.

4.6.1 Planning a hand location

When the eyes look at where an object is located, exteroceptive retinal signals and proprioceptive eye muscle activity specify a unique encoding of the space around them. Kuperstein (1988) argued that this information could be associated with arm muscle activity to put the arm in a configuration that would locate the wrist at where the eyes are looking. This is much like a baby learning to calibrate her visual system with her motor system (see also Held & Bauer, 1967, 1974). In this model, Kuperstein used an adaptive neural network to basically compute an inverse kinematic arm configuration (see Figure 4.13), correlating visual sensations to arm muscle settings using a hetero-associative memory (see Appendix C). In other words, patterns of activations on the eye muscles and retina were associated with patterns of activations of arm muscles through a set of adaptable weights. In order to demonstrate the feasibility of such an algorithm, Kuperstein (1988) tested it on both a simulated robot arm and a real robot arm. In these tests, he placed a high contrast marker on a cylinder and used the center of the visual contrast as the location to which the two cameras should orient.

The algorithm involves two separate phases for the computation. In the learning phase, self-produced motor signals are generated to place the arm so that it is holding the cylinder (how the arm gets to that location is not part of this algorithm). The eyes look at the cylinder, and sensory information is projected through the hetero-associative memory producing computed arm muscle signals. The difference between the actual and computed configuration is determined and then used to change the weights in the hetero-associative memory. Initially, the associated configuration will be quite wrong, but as the weights are updated, the associated configuration improves. In the use phase, the eyes locate the cylinder free in space and, using the weights currently stored in the network, the exact (within a small error) goal arm configuration is generated. Presumably, this goal information is passed onto a trajectory planner that then places the arm at that location and configuration (see discussion of Grossberg VITE model in Chapter 5 for trajectory planning).

The artificial neural network used by Kuperstein is seen in Figure 4.13. Some of the layers are used to recode the inputs before they are presented to the hetero-associative memory. For example, the first layer, at the bottom of the figure, recodes exteroceptive retinal and proprioceptive eye inputs into internal representations. On the bottom left side of the figure, the visual sensation of the cylinder is registered

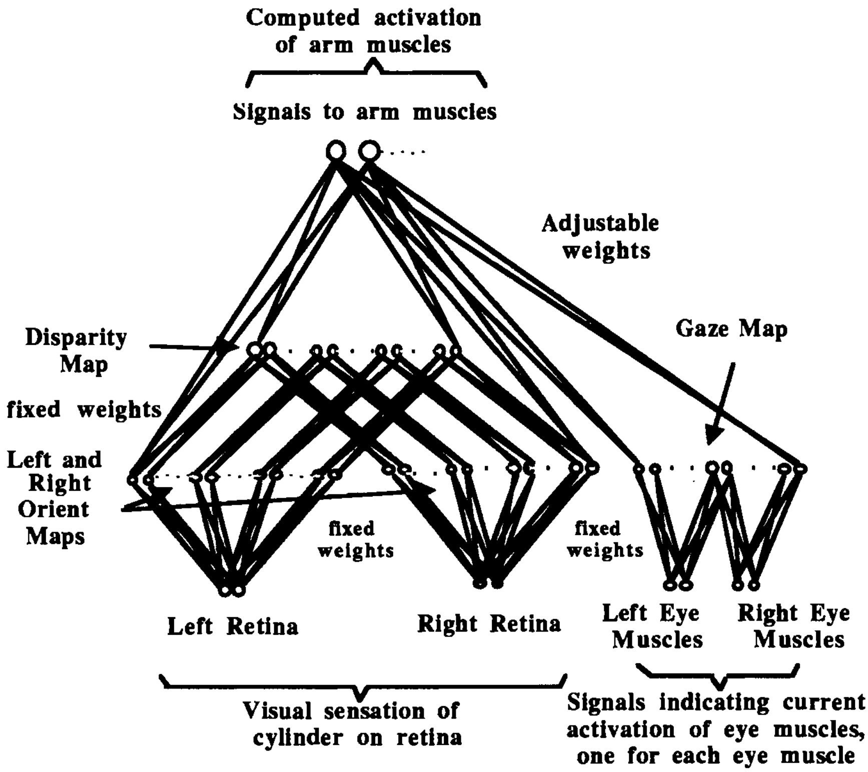

Figure 4.13 Kuperstein's (1988) model of adaptive hand-eye coordination. The visual system consists of two 50x50 receptor retinas being controlled by six muscles for each eye (three pairs of antagonistic muscles). The arm system consists of a three degree of freedom shoulder and two degree of freedom elbow being controlled by ten muscles (five pairs of antagonistic muscles). Fixed algorithms convert the exteroceptive and proprioceptive visual information into inputs for the adaptive neural network. The network associates the visual pattern with an arm configuration, and adjusts the weights in order to reduce the error between the computed values and actual ones. Only 12 of the 318,000 connections are shown between the internal visual representation and the motor representation.

on a left and right retina modelled as two arrays of 50 by 50 receptors. In the figure only two of the 2500 receptors are shown for each retina.

Information from each retina is converted into four orientation maps using a convolution function[5]. By convolving the retinal map with one of four orientation masks (0°, 45°, 90°, 135°), raw intensity values are converted into orientation responses similar to the occular dominance columns that have been noted in visual cortex (Hubel & Wiesel, 1968). A disparity map, in the middle of Figure 4.13, is created by using a simple function that combines pairs of orientation maps, creating a layer of binocular neurons like those found in visual cortex (Poggio & Fischer, 1977). Together, the left and right orientation maps and the disparity map become part of the inputs to Kuperstein's adaptive neural network.

On the bottom right of Figure 4.13, the rest of the inputs into the network are seen. These come from the twelve eye muscles, six for the left eye and six for the right eye. Kuperstein recodes these proprioceptive signals into a unimodal distribution of activity over 100 neurons, creating a gaze map for each eye and one for disparity. In each of the three gaze maps, 600 neurons encode the eye-muscle signal into a representation that has a peak at a different place depending on the activity of the muscles. This conversion puts the inputs into a higher dimensional space, one that is linearly independent.

The top half of Figure 4.13 shows the hetero-associative memory. This part of the network associates the visual inputs (disparity and orient maps) and eye-muscle activation (gaze maps) with an arm configuration. At the top of the figure, the arm is represented by ten muscles (three pairs of shoulder muscles and two pairs of elbow muscles). For this adaptive computation, Kuperstein uses the delta learning rule (see Appendix C) to adjust the weights by comparing the arm muscle values computed by the current settings of the weights to the actual arm muscle values. Using the delta learning rule, he computes the difference between these and adjusts the weights so that the difference will be reduced. It took 3000 trials to learn the inverse kinematics to within a 4% position error and 4° orientation error. On each trial, the arm was place in a random configuration.

Kuperstein used supervised learning for modifying the weights in the adaptive neural network. Kuperstein generated arm muscle settings and compared them to the values produced by the network. When they did not agree, he modified the weights so that the next time the eyes saw that arm configuration, the computed arm muscle settings

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[5]A convolution function simulates the response of a system in which the local effects of inputs may be spread over time and space in the output, e.g., blurring of a lens, echoing of sounds in a room.

were in closer correspondence to the actual muscle settings. Thus, the actual arm muscle settings are acting as a teacher. And while there is no external teacher to make this correlation, there had to be some outside entity that pointed the eye at a given location. In order to accomplish this, he used a high contrast mechanism: the eyes looked at the highest contrast place in space, which in this case, was a marker on the wrist.

Kuperstein's model demonstrates how a computation might be done in the brain to relate visual locations in space to the muscle activity needed to produce a goal arm configuration. Note that he did not actually use the network to place the arm at any one location. Evidence for such visually guided behavior emerging from the relationship of visual stimulation to self-produced movements has been demonstrated in cats (Hein, 1974). One problem with his model is in the nature of the problem he is trying to solve. Relating goal locations to muscle commands requires an inverse kinematic computation. The inverse problem is ill-posed because there are many solutions for arm configurations at a given goal location; his robot will only learn one of these configurations.

Other styles of neural networks are possible. Iberall (1987a) presented a computational model for the transport component using a non-adaptive neural network, called the Approach Vector Selector model. To compute the wrist location goal, a pair of two-dimensional neural networks interacted with two one-dimensional layers, following Amari/Arbib cooperative/competitive models (Amari & Arbib, 1977). As seen in Figure 4.14, Iberall used a pair of two-dimensional excitatory networks to represent the space around the object in polar coordinates (distance r, orientation f) relative to the object's opposition vector. Each node in the excitatory neural networks was a location in this task space. These nodes competed with each other in order to attract the wrist to a good location for contacting the dowel by two virtual fingers. The analysis for VF1 and VF2 was separated; that is, one network represents the perspective of VF1, the other represents that for VF2. Two inhibitory processes interact with these (not shown), allowing gradual build up of an agreed upon solution between the nets. As a 'winner take all' network, possible wrist location solutions compete, with distances and orientations outside the range of the opposition space dying out, and VF configurations that correspond to an effective posture for the given opposition vector reinforcing each other. If the parameters are properly chosen, the Amari/Arbib model predicts that the field will reach a state of equilibrium, where excitation is maintained at only one location.

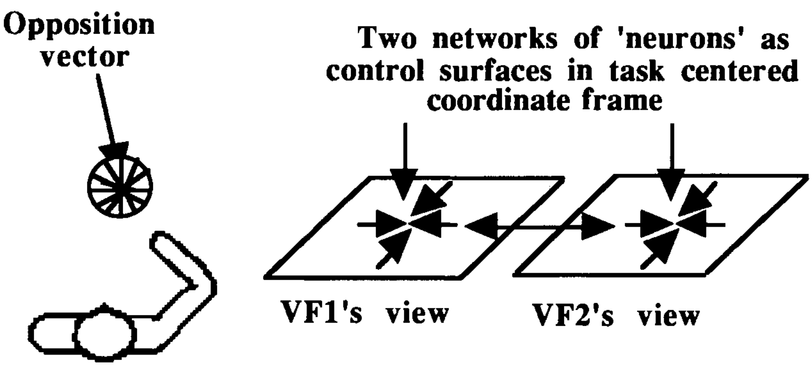

Figure 4.14. Iberall Approach Vector Selector model. The coordinate frame for the computation is task centered around the opposition vector. On the right are shown the two competing networks. Local computations occur at each neuron, receiving excitatory inputs from its four neighbors, from its counterpart in the other network, and from the inputs to the system. Global inhibition keeps the computation below a certain level of excitation.

From measurements taken from the hand of one subject and from estimates on the range of the degrees of freedom of the hand articulators (Kapandji, 1982), a kinematic solution set was calculated and the number of solutions at various wrist locations counted. These solutions were where normals from the pads of VF1 and VF2 were equal in value and opposite in direction and also collinear with the opposition vector. Using the count of potential solutions as input, the Approach Vector Selector computed a location to put the wrist at time of contact. In Figure 4.15, a time course trace of the Selector starts from an initial state and finishes when it has converged on a solution for the wrist position relative to the object. The network of cells is initialized to a zero excitation level, as seen in Figure 4.15a. On the left, the excitatory field VF1 is seen; on the right, the field VF2 is seen. Simulated activity at 11 time-constants after initialization is seen in Figure 4.15b, and at convergence in Figure 4.15c at 27 time-constants after initialization. The peak formed indicates a reasonable (within the constraints modelled) and desired solution for the location of the wrist. Iberall found that higher weights on VF1 were needed than those on VF2 in order to get convergence. This supports the behavioral results showing the thumb being more constrained (see

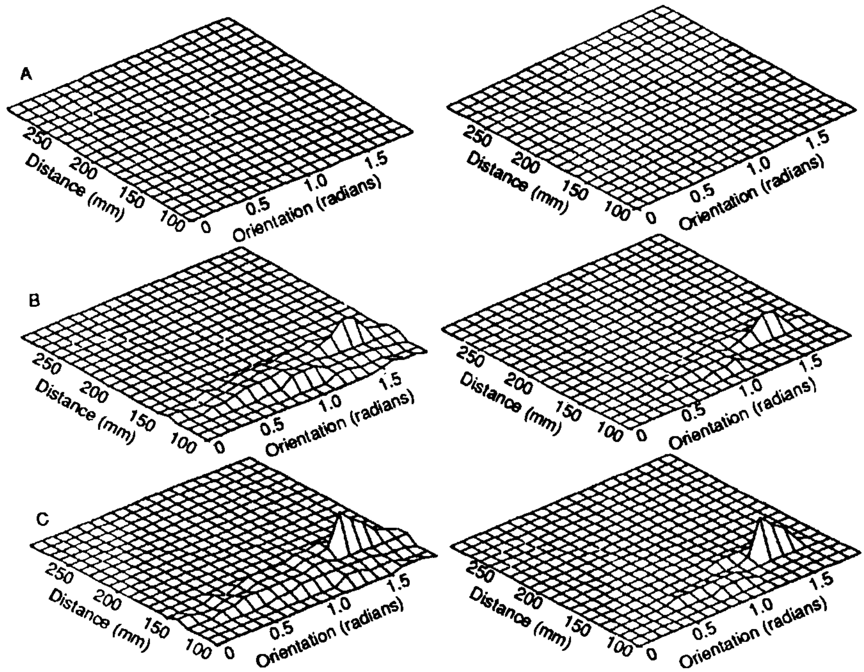

Figure 4.15 Simulation run of Iberall Approach Vector Selector model. A time course trace is seen starting at (a) initial state, then (b) after 11 time-constants, and finally (c) at convergence in 27 time-constants after initialization. The peak formed indicates a reasonable (within the constraints modelled) and desired solution for the location of the wrist. The model has converged on the solution r_d = 140 mm and f_d = 1.4 radians relative to the object (from Iberall, 1987a; reprinted by permission).

Chapter 5).

Since the two excitatory networks computed a wrist location, they had to agree on a location. A good location for the wrist was one where: 1) the VFs could reach the ends of the dowel, 2) the pads were aligned with each other (as a rough approximation of how precision grasping occurs), and 3) the pads were aligned with the dowel. Weights were tuned in such a way that the computed response of a node was active when an input was presented and inactive when the input died out. The input, I, to the field was a map of the solution space, indicating all the locations (r, f) that were reasonable places to put the wrist. Reasonable is used here in the sense that kinematic solutions exist for both VF1 and VF2. This input represents a very large solution space, because it could be defined over all possible kinematic solutions for all object sizes that could be grasped.

4.6.2 Orienting the palm

While the arm transports the hand to the object, the hand is oriented. This can be done from the shoulder joints through all the more distal joints to the grasping surfaces of the hand. With respect to wrist angle, static isometric force studies have shown that the tendons of the finger extensor muscles are too short to allow maximum grasping force when the wrist is fully flexed. For a forceful grasp, it has been noted that optimal wrist angles exist (Hazelton et al., 1975, Bunnell, 1942).

Constraints on orientation, such as biomechanical ones and intended actions, can affect grasp planning. Rosenbaum, Vaughan, Barnes, Marchak and Slotta (1990) examined the planning of complex movements in terms of awkwardness of postures. Subjects were asked to pick up a horizontal two-colored bar using either an overhand grasp (coming down on the bar, as seen in Figure 4.16a) or an underhand grasp (coming up on the bar, as seen in Figure 4.16c). They then had to place the bar vertically either on its gray (see Figure 4.16b) or black end (Figure 4.16d) either to the left or right. All subjects used a grasp that left their wrist, elbow, and shoulder joints in a comfortable posture at the end of the place movement. In some of these conditions, it meant the initial posture was more awkward. For example, it is initially awkward for a right-handed subject to use an underhand grasp to place the black side on the right side of the table. Initially it would be less awkward to use an overhand grasp for the same task; however, placing the bar from this posture would be even more awkward. Rosenbaum and colleagues then asked subjects to grasp the horizontal bar and either place it vertically on the table or into a suspended holder. They noted that, without restricting the subjects initial grasp posture, 6 of the 12 subjects twirled the bar so that they could comfortably grasp and place the bar. In a third experiment, restrictions were placed on the subjects, urging them to 'grab the bar in the middle, holding it like a tennis racket.' In this experiment, some of the tasks required subjects to perform two sequence moves (e.g., grasp bar and place its black side on the table, then place its white end in the suspended holder). Of the sixteen combinations of one and two sequence moves, subjects consistently used postures that reduced awkwardness at the end of the first placement, even in the tests where two moves had to be made in sequence. In this case, it appears that planning is occurring for only the first part of the task, not the second part. This agrees with the observation of Henry and Rogers (1960) that later parts of a movement sequence can be programmed after movement has been initiated.

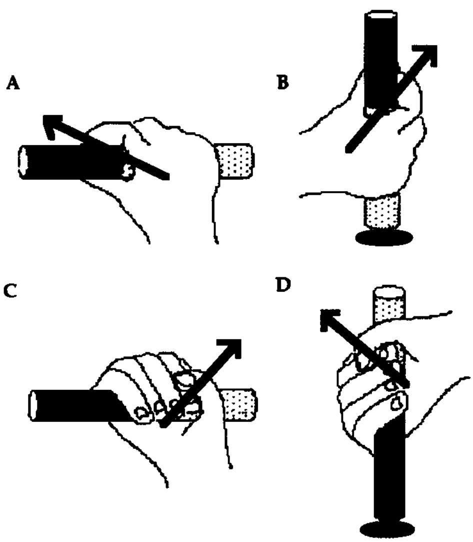

Figure 4.16 Rosenbaum et al. (1990) horizontal grasp experiment. The arrow is the z-axis perpendicular to the palm; this shows the orientation of the palm. (a) Two colored bar is grasped overhand. (b) Bar is placed on the table with its grey side down. (c) Bar is grasped underhand. (d) Bar is placed with its black side down.

The results of Rosenbaum et al. can be viewed in terms of opposition space. In the third experiment, the experimenter's placed a restriction on the subjects, urging them to 'grab the bar in the middle, holding it like a tennis racket.' In not specifying the orientation of the wrist, subjects chose either a palm opposition or a pad opposition. Using the latter, they were able to 'twirl' the bar into the required orientation for the task. With the imposed restriction in the third experiment, subjects used palm opposition. The direction of palm had to be within the constraints of the task; i.e., it had to be rotatable within the confines of the wrist's range of mobility. In Figure 4.16, the z-axis along which palm opposition occurs is shown, extending from the palm.

As an aside, it is easy to observe 'twirling', i.e., reorienting objects for a given task using degrees of freedom at the wrist or at the fingers. It happens when people pick up pens and pencils to write. When the point is directed away from a right-handed person, that person either picks it up with the thumb on the left of the pencil's body and twirls it into position between the fingers, or else picks it up with the thumb on the right of the pencil's body and reorients the pencil with adduction of the shoulder and supination of the forearm. We discuss twirling and other object manipulations in Chapter 6.

Rosenbaum and colleagues termed the finding of initially awkward postures for the sake of finally comfortable end postures, the end-state comfort effect. In addition, they noted a thumb-toward bias effect, in which the base of the thumb was oriented to the end of the bar to be placed on the target. Reaction times to initiate reaches were longer when the thumb was away from the pointer than when the thumb was oriented towards the pointer; the thumb-towards bias was suggested not to reflect visibility or perceptual factors, but attentional ones (Rosenbaum, Vaughan, Barnes & Jorgensen, 1992). Further, Rosenbaum and Jorgensen (1992) demonstrated a sequential or hysteresis effect, in that the probability of using an overhand grip was dependent on previous grips used in a structured sequence, i.e., subjects persisted in using a previous grip. They suggested that there is a computational cost in selecting a new grasp.

The orientation of opposition space was addressed directly by Stelmach, Castiello and Jeannerod (1993). They had subjects grasp a prism 6 cm long, triangular in cross-section, by the ends, using pad opposition between the thumb and index finger. When the object was placed parallel to the subject's midline, all subjects grasped with the forearm in a semipronated position. There were six orientations of the object, as shown in Figure 4.17. As the object was rotated clockwise

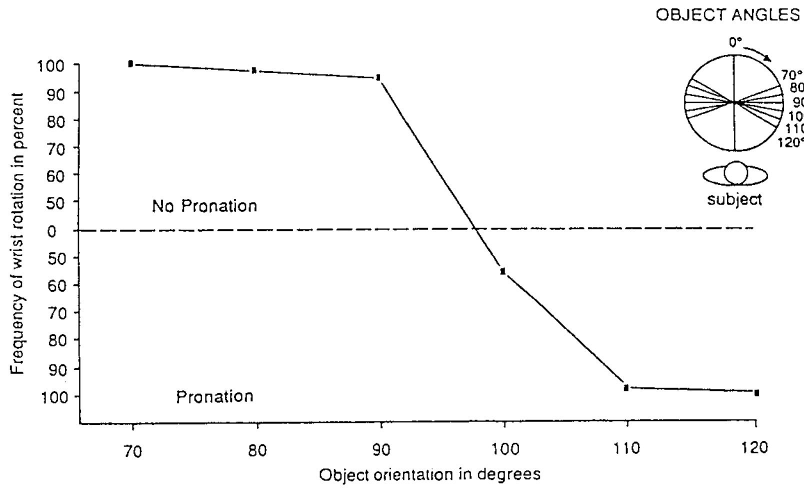

Figure 4.17 Percent of trials with pronation of the forearm or not, for each object orientation. Note when the object is oriented parallel to the frontal plane of the body, there is no pronation, and the palm is oriented away from the body. When the object is rotated beyond 90 degrees, there is a transition to an entirely different arm configuration, with glenohumeral rotation and forearm pronation, orienting the palm towards the body (from Stelmach, Castiello & Jeannerod, 1993; reprinted by permission).

from 70 degrees, the orientation of the grasping surfaces of the finger pads rotated correspondingly, with the thumb closer to the midline than the index finger. At some point, when the object was rotated beyond an orientation parallel to the frontal plane (or beyond perpendicular to the midline sagittal plane), there was a major realignment of the arm, whereby the forearm pronated and there was rotation about the glenohumeral joint (abduction and internal rotation). With this reorientation of the palm so that it faced the midline, the relative positions of the finger and thumb were switched, i.e., the index finger was closer to the midline that the thumb. Summarized in Figure 4.17, across all trials, for object angles of 70, 80, or 90 degress, almost all grasps were executed without forearm realignment. At 100 degrees, approximately half the trials demonstrated some forearm pronation and an altered orientation of the palm of the hand for grasping with the finger pads. For 110 and 120 degree object orientations, all subjects systematically demonstrated this strong pronation of the forearm, with the palm oriented towards the body. An examination of the kinematics of these movements, and for perturbations of object orientation is provided in the next chapter.

4.7 Summary of Planning an Opposition Space

In order to perform the simple task of lifting an object such as a hammer, preparatory processes related to the organization and planning of the upcoming movement occur in the CNS, coordinating highly complex activity. A task plan, constructed as a coordinated control program or as something close to such a program, is needed to tie together the serialization of multiple sub-tasks, such as transporting the hand to the correct location and orientation, and shaping the hand into a suitable posture.

In this chapter, task plans from a variety of fields have been examined. A robotic task plan makes distinct the phases of a task. In addition, it puts forth a language, complete with a hand coordinate frame for interfacing to the robot arm. Finally, it suggests a task plan can be constructed as a skeleton plan that is filled in with more details for a feedback controller. The Arbib coordinated control program is a task plan that models the brain as a distributed controller. A hierarchical task plan such as TOTE, points out that a task plan must have contingencies for error. Finally, a neural task plan suggests how plans such as these could be mapped out across regions of cortical and sub-cortical areas in the CNS. This fits in with brain studies which show premovement activity in parietal, frontal and subcortical regions.

The more complex the movement, the longer the reaction time. Here, complexity includes both the number of things that must be done, as well as the time it will take to perform the task. However, in terms of planning, it is hard to say how far movements are planned in advance; some complex movements seem to be only partially planned prior to movement. This means that further movements can be planned during initial movement.

In order to accomplish a task plan, three issues have been addressed: perceiving task-specific object properties (including the <u>opposition vector</u> based on knowledge about task requirements and task mechanics), selecting a grasp strategy, planning a hand location and orientation. Experimental evidence suggests that intrinsic object properties, such as size and shape, and extrinsic object properties, such as object location and orientation, are perceived prior to movement. The object properties perceived are specific to the task demands. Importantly, knowledge about the function and behavior of objects is stored over time, and our ability to anticipate simplifies the planning process. For example, the thumb and index finger do not have to grasp the object at precisely the same time. One can anticipate how to 'push' the object into the grasp. If the goal is to impart motion to the object, anticipation of those translations and rotations is part of the planning process. Planning a posture includes the anticipated motions in multi-operation tasks.

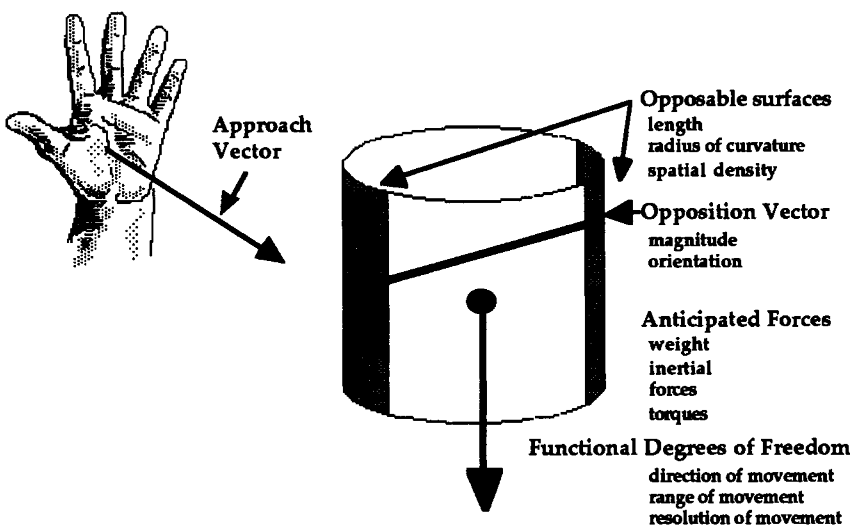

Figure 4.18. Approach vector for the hand, relative to the opposition vector seen in the object.

A grasp strategy must be chosen in accordance with the task, so that functionally effective forces of a given direction and magnitude may be applied. In order to do this, one first perceives the opposition vector. The term 'grasp strategy' refers to selecting appropriate opposition types, mapping virtual fingers into real anatomical fingers, and determining opposition space parameters. Mappings between object and task characteristics and hand postures have been modelled using expert systems and using neural networks. Expert systems make explicit the rules of these mappings; neural networks can learn the rules. Both depend on experimental data that demonstrates how virtual finger mappings depend on object properties.

Besides choosing a grasp strategy, a location and orientation in space for the hand must be planned, given the opposition vector and grasp strategy. Critical to grasping the opposable surfaces is transporting the hand to a location and orientation near the object to make this possible. An approach vector can be constructed between the hand and the opposition vector (see Figure 4.18). This in effect, describes the task space, relating the hand to the object. It has been shown that this location could be a palm location generated by an arm configuration that has been calibrated to the eye muscle coordinate frame. An alternative solution is a preplanned location and orientation for the palm where the grasping surface patches of virtual finger 1 and 2 can align their force vectors with the opposition vector. Importantly, the chosen palm location and orientation are affected by both task constraints and object properties.

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Chapter 5. Movement Before Contact

"If you don't know where you are going, how can you expect to get there?"

- Basil S. Walsh

Our subject is about to pick up a hammer placed directly in front of her midline. Movement begins and, as the arm reaches out, anticipatory shaping of the fingers occurs, appropriate for the task at hand. Then, the fingers begin to enclose around the hammer. All of this observed movement is effected for the goal of the task, i.e., grasping the hammer.

From movement initiation until first contact with the hammer, the goal of capturing the hammer into a stable grasp requires that the hand be configured appropriately. In Chapter 4, a distinction was made between task planning and trajectory planning. Task planning, prior to movement initiation, was examined and it was observed that key planning variables were opposition space parameters given the task requirements and object characteristics. In this chapter, the focus is on trajectory planning and the setting up of an opposition space. An overview of the issues involved in trajectory planning is presented, and a conceptual model for transforming a goal into motor comamnds is discussed. We then consider control of unrestrained motion of the arm in pointing and aiming tasks. Computational models and experimental results related to coordinate transformations are discussed, including the key roles for proprioceptive and visual information in guiding the movement. When the hand is added to the arm as an effector for grasping and manipulation, evidence is provided that the arm acts differently than when the arm is moving alone in aiming and pointing tasks. The kinematics of reaching and grasping are examined as a function of task requirements and object properties. Focussing on the hand, we consider hand opening to maximum aperture (preshaping) and closing to first contact (enclosing) as unique phases, noting that the precise functions of enclosing after maximum hand opening remain elusive. Trajectories are considered for different grasp types, pad and palm opposition, and the role of visual and proprioceptive information in monitoring the free motion phase before contacting the object. The two phases prior to contacting the objects are viewed in terms of Greene's ballpark model, introduced in Chapter 3. During the move fast phase the opposition space set up is placed 'in the ballpark'; during the drive fingers guarded phase, contact is anticipated, and there is continued orientation and positional adjustment until the hand grasping surfaces make contact on specific locations, given the opposition(s) used.

5.1 Overview of Trajectory Planning

Arbib's (1985) coordinated control program (CCP) was presented in Chapter 3 as a conceptual model that addressed how the arm and hand might be controlled during reaching and grasping. In Figure 5.1, the lower section of the coordinated control program has been extracted in order to focus on the motor aspects of the program.

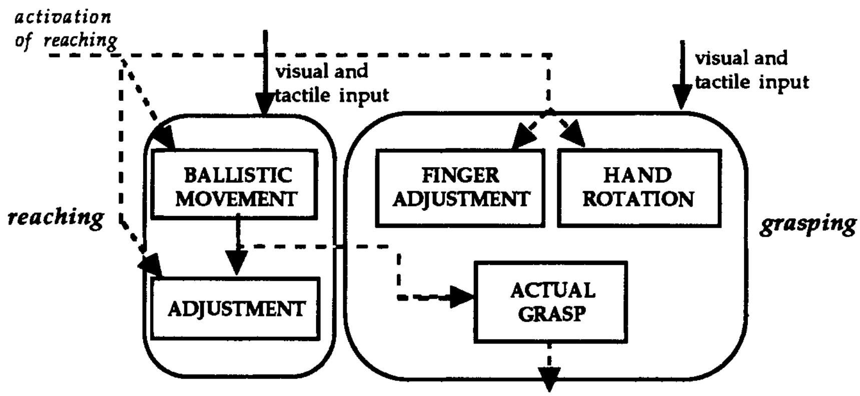

Figure 5.1 The motor aspects of the coordinated control program. On the left, the two phases of the reaching component are seen. On the right, the grasping component involves the adjustment of the fingers into a suitable shape, rotation of the wrist, and then the actual grasp on contact (from Arbib, 1985; adapted by permission).

In this chapter, trajectory planning is analyzed for the arm (left side of Figure 5.1) and the hand (right side of Figure 5.1), paying careful attention to the control mechanisms, the computations that have to be performed to support these control mechanisms, and the temporal, spatial, and functional relationships between these schemas. The process of transporting a hand to a location (or for that matter, opening and closing the fingers) can be thought of as <u>endpoint trajectory generation</u>, and it entails an analysis at various levels of motor control. This issue is studied at levels that include joint angles, joint torques, muscle activation, and neural innervation.

One question that might be asked is whether all arm movements exhibit two phases as Arbib modelled for reaching movements. Jeannerod and Biguer (1982) made a distinction between simple and complex movements. In the context to which they were referring, pointing to a location in space is simple because it does not involve interaction with the environment. Reaching and grasping in this context would be complex, because the end goal involves interactions with environment (the 'actual grasp' schema in Figure 5.1). While the arm is transporting the hand to a location near the object (the 'ballistic movement' schema in the figure), the hand is preshaping in anticipation of the actual grasp. The arm continues to move during the actual grasp (the 'adjustment' schema).

The 'ballistic movement', 'finger adjustment', and 'hand rotation' schemas are examples of unrestrained or free space motions. Once the hand touches the object, motion changes from being unrestrained to a compliant motion, necessarily having to comply with the object and its support surface. For example, in order to lift the object, the posture effected by the hand must be able to apply forces against the object surfaces that counterbalance the object's weight, all the while not crushing the object. This issue of force application to an object and restrained or compliant motion will be dealt with in Chapter 6.

In looking at the CCP, an important issue is the nature of the control law used within each schema. For example, the term 'ballistic movement' was used. A ballistic controller is a 'bang-bang' controller, with the agonist muscles turning on to initiate the movement, and near the end, the antagonist turning on to decelerate the arm. This is similar to a feedforward controller, where a trajectory is preplanned. An alternative is a feedback controller, which continually senses the difference between a desired and current state of a system and makes adjustments to reduce the difference.

In dealing with feedback control, the nature of sensory signals is important, and in the human nervous system, sensory signals come from interoceptors, exteroceptors and proprioceptors. Interoceptors are sensitive to internal events and serve to maintain physiological homeostasis[1]. Exteroceptors are sensitive to external stimuli and include vision receptors and the skin mechanoreceptors, which are responsive to crude touch, discriminative touch, skin deformation, pain,

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[1]We deal with interoceptors minimally in this book (e.g., in Chapter 6 we note innervation to cutaneous mechanoreceptors and vasodilators in the blood vessels of the hand).

and temperature. Proprioceptors provide information about the relative position of body segments to one another and about the relative position and motion of the body in space, including information about mechanical displacements of muscles and joints. Proprioceptive receptors traditionally include joint receptors, tendon receptors, and muscle spindles. For our purposes, we exclude vestibular contributions to proprioception, acknowledging their critical contributions. Integrated with other efferent and receptor information, joint and muscle receptors are critically important during both free motion and compliant motion. Skin mechanoreceptors are also important in feedback control for force regulation and for providing information concerning motion about the underlying joints (skin receptors are discussed in Chapter 6). For grasping objects, these all contribute to information about skin stretch, joint motion, contact with objects, object properties, compliance, mechanical deformations and interactions with the object.

Once a task plan such as the CCP is constructed, it must be carried out by the CNS. The neural model of Paillard, as was seen in Figure 4.4, separated the programming (trajectory planning) and execution of the movement from the task plan. A key player between plan and execution is the motor cortex. Over a hundred years of neurological stimulation of cortical areas of the brain have indicated that the motor cortex is topographically organized; that is, there is a body representation arranged in an orderly fashion, from toes to head, as seen in Figure 5.2. This is true for the somatosensory cortex as well. Those parts of the body requiring fine control, such as the hands and the face, have a disproportionately large representation. An important question is what is the function of motor cortex and whether muscles, movements or forces are being represented. In general, it has been observed that single neurons can influence several muscles, and also that individual muscles can be represented more than once in motor cortex. For example, Strick and Preston (1979) found two anatomically separate hand-wrist representations in the motor cortex. Are these representations functional? Muir and Lemon (1983) recorded neurons in the hand area of the motor cortex while recording EMGs from the first dorsal interosseus muscle (a muscle active both in pad and palm opposition). They found that motor cortex neurons responded for pad opposition, but not for palm opposition. As noted in Chapter 4, however, the motor cortex is only one of many distributed regions in the CNS. The neural control of grasping is examined in greater detail in this chapter.

The coordinated program suggests that a target location is sent to

Figure 5.2 Topographical organization of motor cortex. Note large representation of hand (from Kandel & Schwartz, 1985; reprinted by permission).

the reaching schemas, and the target object size to the grasping schemas. A fundamental question is how the CNS represents information and converts it into a motor command. For example, if the task is to place your wrist at a location close to an object in order to grasp and lift the object, then six coordinates in an extrinsically-defined coordinate frame will uniquely describe the position (x,y,z) and orientation (a,b,g) of that three-dimensional location. However, the arm itself has many degrees of freedom, and there are also many potential levels of motor control. At the joint level (as seen in Appendix A), the arm has about 11 degrees of freedom (3 at the pectoral girdle, 3 at the shoulder, 2 at the elbow, 1 at the radioulnar joint, 2 at the wrist). Since the task has six degrees of freedom and the arm has 11 degrees of freedom, five extra degrees of freedom are present above the task specification. This makes the solution of a computation indeterminant, because the number of degrees of freedom available in the controlled system exceeds the number of degrees of freedom needed to specify the task. At the muscle level, the problem is even more complicated, since there are about 33 muscles, some having multiple compartments and attachments. Thousands of muscle fibers combine to form these muscles. Thus at the muscle level, there are at least 27 extra degrees of freedom above the task specification, and at the muscle fiber level, there are thousands of extra ones. At any level of analysis, therefore, there are many possible ways to achieve the same goal. When a controlled system has such redundancy, one unique solution does not exist for that the controller; therefore the problem is ill-posed.

A further complication is that many degrees of freedom in the human arm and hand are coupled; i.e., there are nonlinear interactions between degrees of freedom. Interdependent motions are noted for the joints of the pectoral girdle, and muscles can be seen to contribute to more than one degree of freedom at a joint (see Appendix A). For example, Soechting and Terzuolo (1990) discussed a task where shoulder and elbow flexors are required to counteract gravity. They pointed out that the posture could be maintained using the brachioradialis (an elbow flexor) and anterior deltoid (a shoulder flexor), or alternatively, using the biceps (an elbow and shoulder flexor). What mechanism is the CNS using for making such a decision? Bernstein (1967) argued that having redundant degrees of freedom makes it easier to control the arm, suggesting that actions are organized as synergies in order to reduce the number of degrees of freedom to be controlled[2]. He argued that action-related proprioceptive input is necessary since the CNS cannot foresee and compute forces acting on several simultaneous joints.

Finally, there are an infinitely large number of spatial paths that the hand could follow in reaching towards an object. And for any given path, there are an infinitely many velocity profiles that could be used. Recalling Greene (1972), the choice can be constrained to approximations by an executive, with lower centers fine tuning the ballpark solution.

One way to reduce the degrees of freedom problem is to use a cost function as a measure of the 'goodness' of a solution. This performance criteria can be done on a variety of measures, such as the minimal movement time, torque, potential energy (Massone and Bizzi,

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[2]A synergy is a group of muscles acting within a functional and coherent unit.

1989), mean-square error of jerk[3] (Flash and Hogan, 1985), and mean-square error of torque-change (Uno, Kawato, Suzuki, 1989). A cost function constrains the potential hand paths and velocities, in that the CNS makes a selection out of the infinite number of possible by minimizing this measure. One such model is the 'minimum jerk model' (Flash and Hogan 1985), which suggests that the square of the jerk of hand position integrated over the entire movement is minimized. Flash and Hogan showed that the trajectory uniquely defined by this criterion function agrees with experimental data in various regions of the workspace[4].

In summary, trajectory planning involves transporting the hand to a location by a controller. Cortical areas, such as the motor and somatosensory cortex, are critical for neural control. Sensory information is provided by exteroceptors and/or proprioceptors. How the CNS transforms a goal into motor commands is a critical question, particularly in light of the fact that so many degrees of freedom exist at the joint level, the muscle level, and particularly at the muscle fiber level. Exacerbating this are problems such as motor equivalency, coupled degrees of freedom, and an endless number of solutions. Cost functions have been proposed as a way to constrain the potential number of solutions.

5.2 Transforming a Goal into Motor Commands

Goals must be transformed into motor commands. If the goal is specified in some extrinsic coordinate reference frame, the CNS could possibly compute an arm trajectory also in an extrinsic coordinate frame. This trajectory could then be transformed into an intrinsic coordinate frame (e.g., joint angles), and then into intrinsic dynamics (e.g., muscle activity). Along this hierarchical scheme and coming from a robotics framework, Uno, Kawato and Suzuki (1989) put forth a computational model for voluntary movement as seen in Figure 5.3. Starting from the environmentally-defined goal (e.g., target location, object size), they proposed the following computations:

1) <u>determination of desired trajectory</u> - the goal of the movement, such as picking up a coffee mug in order to drink from it, is translated into an extrinsic kinematic coordinate frame for a path

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[3] <u>Jerk</u> is the rate of change of acceleration.

[4] The <u>workspace</u> is a collection of points to which the hand of an arm can reach.

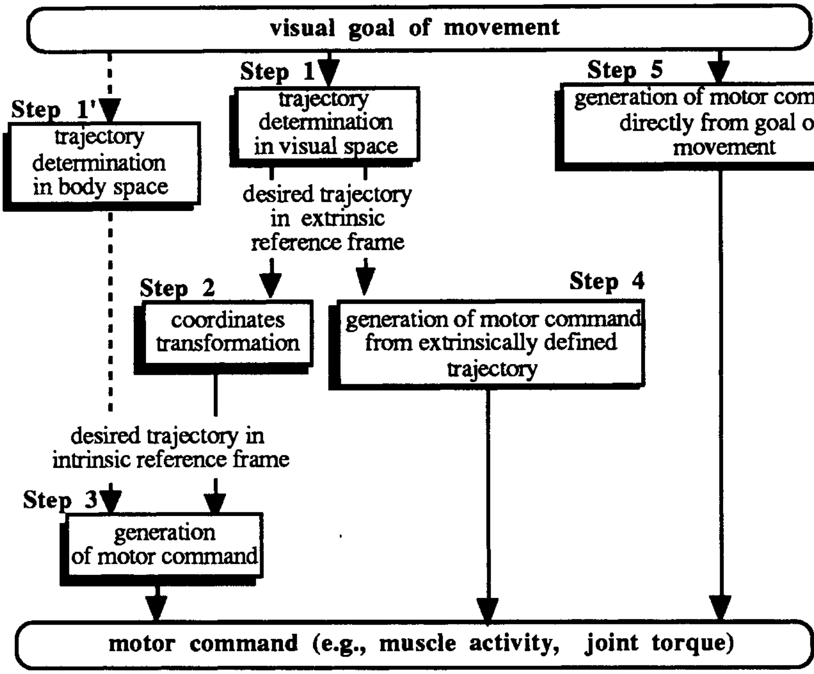

Figure 5.3. Computational model of voluntary movement. Starting from a desired goal, a trajectory is computed in an extrinsic coordinate frame (step 1). The trajectory is transformed into an intrinsic coordinate frame (step 2), which in turn is used to generate motor commands (step 3). Alternatively, motor commands can be generated directly from the extrinsically defined trajectory (step 4), or even from the goal itself (step 5). Another alternative would be to plan the trajectory directly in joint space (step 1') (from Uno, Kawato and Suzuki, 1989; adapted with permission).

involving a sequence of hand positions, and a speed or time sequence of the movement along the path. This is step 1 in Figure 5.3

2) coordinates transformation - the desired trajectory is translated into an intrinsic kinematic coordinate frame of body coordinate commands, such as joint angles . This is step 2 in Figure 5.3.
3) generation of motor command - body coordinate commands are translated into an intrinsic dynamic coordinate frame of muscle torque commands that can coordinate the activity of many muscles. This is step 3 in Figure 5.3.

Step 1 suggests that the CNS plans movements in hand space, thus generating a trajectory involving hand positions and speeds along a path in a body or world coordinate frame. The reason for this is two-fold. The first has to do with the goal of the task, which is to bring the hand into contact with the object. If the object is in a world coordinate frame, then planning hand locations in that same coordinate frame makes the computations easier. The second has to do with the grasping space of the performer. How can accidental contact with other objects in the vicinity be avoided, and how can a trajectory be planned through a cluttered environment? If the objects are in a world coordinate frame, then planning in the same reference frame is easier. Transforming this desired trajectory into joint space (step 2) and generating the motor command (step 3) involves translating from that coordinate frame into the space within which the actual movement is being driven. If the control variables are kinematic ones (step 2), this is an inverse kinematic[5] problem. If the control variables are dynamic ones (step 3), such as joint torques over time, this is an inverse dynamic problem.

Such step by step computations, while logical, are inefficient and most likely, not biological. For one thing, coordinate transformation computations contain errors, so avoiding re-representations is advantageous. Alternatively, motor commands can be computed directly from the desired extrinsically-defined trajectory (step 4) or even from the goal of the movement (step 5). Another alternative is to plan directly in joint space (step 1'). While seemingly more complicated, it is possibly more natural, in the sense that, through joint and muscle proprioceptors, these are variables that the CNS has access to. Atkeson & Hollerbach (1985) pointed out that if a trajectory is determined in an extrinsic coordinate frame (step 1), the path of the hand would follow a straight line (in a world coordinate frame). On the other hand, if the trajectory generation is computed in joint angles directly (step 1'), the hand would follow a curved path. In behavioral experiments, both have been observed (see Section 5.3).

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[5]The forward kinematic problem computes endpoint kinematic variables (e.g., wrist position) from joint kinematic variables (e.g., shoulder and elbow joint angles). The inverse kinematic problem computes the shoulder and elbow joint angles from a given wrist position.

5.3 Control of Arm Movements

As noted earlier in this chapter, simple movements not involving contact with the environment may be distinct from more complex movements such as grasping, which involve configuration of the hand and complex interactions with the environment. In this section, control of the arm is looked at, comparing pointing movements with aiming movements making contact. Various computational models for transforming goal locations into motor commands are examined.

5.3.1 Spatial transformations

Behavioral studies provide some evidence for the nature of transformations in biological systems. Development of visuomotor control requires experience with both movement and vision together. Monkeys raised without seeing their own motions are unable to perform accurate reaching movements (Hein, 1974; Held & Bauer, 1967, 1974). They are unable to map between visual space and motor coordinates for limb control. Recalling the Kuperstein (1988) model discussed in Chapter 4, integrating visuomotor control of head and eye movement with proprioceptive control of limb movement requires the specific experience of viewing the moving hand[6]. Jeannerod (1988, 1989) studied the mapping between the extrinsic coordinates computed for target position (the 'visual map') and the position of the moving limb with respect to the target (the 'proprioceptive map'). He suggested that there must be a comparison of target position relative to the body and the moving limb position relative to the target. An important mechanism for superimposing the visual and proprioceptive maps is the process of foveation, whereby the gaze axis is aligned with the position of the target in space. Provided the hand is also visible at the same time, foveation will align the two maps. A complementary possibility is that 'tactile foveation' will also align the visual and proprioceptive maps. A key brain area involved in this superposition of visual and proprioceptive maps for accurate reaching is the posterior parietal cortex. Visually directed hand movements are impaired in human patients with lesions to this area; as well, they may have a variety of other spatial processing deficits and problems with oculomotor control to visual targets (Perenin & Vighetto, 1988;

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[6]Held and Bauer (1974) noted that in addition to the reaching deficits, these animal reared without vision of the moving hand also showed deficits in the tactile guidance of grasp, with fumbling movements once contact is made.

Jeannerod, 1988). The reaching movements are inaccurate and much slower, having lower peak velocities and longer deceleration phases. Thus, the posterior parietal cortex is implicated in disruption of the convergence of visual and proprioceptive maps for visually guided reaching.

Other evidence has been observed in behavioral pointing studies for a mapping between extrinsic and intrinsic coordinate frames (step 2). In Soechting and Terzuolo (1990), subjects were asked to remember a target's location, and then asked to point to that remembered spot in the dark. The distance and direction of the target were the extrinsic measures while intrinsic measures were the shoulder and elbow joint angles in terms of angular elevation and yaw. Subjects were able to point in the correct direction but there were errors in the radial distance from the shoulder, ranging from 6.7 to 11.7 cm average root mean square total error in each subject. Soechting and Terzuolo argued that the errors were due to the transformation between extrinsic and intrinsic coordinates, and suggested that the problem is solved only approximately, thus leading to predictable distortions. Soechting and Flanders (1991) showed that for pointing tasks, a spatial location is first transformed from head centered to shoulder centered spatial coordinates. The location is then redefined in an intrinsic kinematic framework by two separate channels that convert target azimuth (horizontal direction) into intended yaw angles of arm in sagittal plane when the hand is at the target, and target elevation and distance into arm segment elevation angles. The difference between current and intended arm angles is then transformed into a motor command signaling direction of hand movement. The error patterns suggest that the CNS uses linear approximations of the exact nonlinear relation between limb segment angles and target location[7].

Separate encoding of distance and direction was obtained in motor memory research in the 1970s, using linear or lever positioning tasks. In such tasks, blindfolded humans grasped a handle using palm, pad or side opposition, and moved to a preselected or experimenter-defined endpoint. Then, either immediately or after some filled or unfilled retention interval, the individuals were asked to reproduce the distance or location, from a new or different starting location. Evidence supported a qualitatively different memory for location than distance (subjects are better at reproducing locations than distances), and that there were different patterns of forgetting of location and dis-

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[7]Separate planning channels may also exist for direction, amplitude and force (Favilla et al., 1989; Riehle & Requin, 1989; Rosenbaum, 1980).

tance as well (Keele & Ells, 1972; Laabs, 1973; Marteniuk, 1973).

More recently, neural evidence has been found for the notion that distance and direction are encoded separately (Georgopoulos, Kettner, & Schwartz, 1988; Kettner, Schwartz, & Georgopoulos, 1988; Schwartz, Kettner, & Georgopoulos, 1988). In these studies, rhesus monkeys were trained to reach forward and press buttons in a three-dimensional workspace. The placement of the targets allowed free motions from the resting position (center and in front of the animal's body) to 8 periperal targets. Recording from motor cortex, Schwartz et al. (1988) found an orderly change in frequency of discharge of a majority of the cells with direction of the reaching. A single cell's activity varied approximately as a cosine function of the movement direction, centered on one preferred direction that varies from cell to cell. Each cell emitted a graded signal for a broad range of movements, and each movement evoked a complex pattern of graded activation that varied with movement direction. Georgopoulos et al. (1988) suggested that motor cortical neurons are signaling a vectorial 'vote' with a direction in the cell's preferred direction and a magnitude proportional to the change in the cell's discharge rate associated with the particular direction of movement. The vector sum of these contributions, the neuronal population vector, is the outcome of the population code and points in the direction of movement in space. In addition, in comparing a time series of the population vector to the instantaneous velocity of the movement, the direction of the vector points in the direction of the movement, and even is an accurate prediction of the upcoming movement. Georgopoulos et al. (1988) showed an example where the population vector formed 160 ms before the movement began. Kettner et al. (1988) showed that steady state activity of motor cortical cells is modulated in orderly fashion with active maintenance of hand position in space.

In terms of specific neural areas, area 5 of the parietal association area (Kalaska, 1988) and the dorsal premotor cortex have several response properties similar to motor cortex (see above), as well as activity of the cerebellum (Kalaska et al., 1983; Kalaska, 1988; Fortier, Kalaska & Smith, 1989). It is known that parietal regions directly and cerebellum indirectly (via thalamus) connect with motor cortex (Strick & Kim, 1978; Caminiti et al., 1985). For monkeys making reaching movements, Kalaska and Crammond (1992) showed overlapping and sequential activity in the following cortical areas, prior to movement initiation: premotor cortex (Area 6), primary motor cortex (Area 4), posterior parietal cortex (Area 5), then somatosensory parietal cortex (Area 2). The firing patterns in Area 5 in particular are paradoxical; i.e., it fires after the motor cortex. This is puzzling because this parietal region is believed to be upstream from the motor cortex, yet it fires after the motor cortex, according to the upcoming movement direction (see also Georgopoulos, 1990). Kalaska and Crammond speculate that Area 5 in posterior parietal cortex could be contributing simultaneously both to kinesthetic perception and to motor control of limb kinematics.

At levels below the motor cortex, there is neural integration at the spinal level. Movements initiated by supraspinal structures engage spinal 'reaching' circuits. Propriospinal neurons are selectively engaged during reaching movements and receive monosynaptic inputs from several supraspinal sources, via corticospinal, reticulospinal, rubrospinal and tectospinal tracts (Illert, Lundberg, Padel, & Tanaka, 1978), sending outputs to target motoneurons. In addition, they send ascending collaterals to the lateral reticular nucleus (Alstermark, Lindstrom, Lundberg, & Sybirska, 1981) which projects to the cerebellum, reflecting on going activity to cerebellum about the evolving movement. Sectioning the output of these propriospinal neurons at C3-C4 levels in the cat results in abnormal reaching, with normal grasping. Similar results are obtained with removal of the corticospinal input to the propriospinal neurons (Alstermark et al., 1981). Rapid responses to visual perturbation of direction of reaching in cats (from 83-118 ms) has been attributed to descending influences on C3-C4 from a retino-tectospinal or retino-tectoreticulospinal pathways (Alstermark, Gorska, Lundberg & Pettersson, 1990). Related results have been obtained with tetraplegic humans, with complete symmetrical sections who have normal grasping but abnormal reaching; voluntary shoulder control may be used to compensate for paralysis of muscles controlling the elbow, so that the hand can be transported to the appropriate location (Popovic, Popovic & Tomovic, 1993; Popovic, personal communication, May 13, 1993).

At the level of the motor command, various control variables have been suggested in the history of motor control, such as muscle length (Merton, 1953), muscle stiffness (Houk, 1978), and resting length between agonist/antagonist (Feldman, 1986) (see Nelson, 1983 for an excellent review). The mass-spring model (Bernstein, 1967; Bizzi, 1980; Feldman, 1986) argues that the CNS takes advantage of the viscoelastic properties of muscles, which act as tunable springs. A spring follows the mass-spring law:

$$F=K\partial X \tag{1}$$

where F is force, K is stiffness of the spring, and ∂X is the change in displacement that occurs when the force is applied. The agonist and antagonist muscles can be viewed as a pair of opposing springs whose equilibrium state[8] determines the joint angle. Movement occurs by varying the equilibrium point over time, changing the relative tensions of the two opposing springs. An equilibrium configuration is defined for a given value of muscle activation as that position where the forces of opposing muscles generate equal and opposite torques about the joints (Hogan 1985). Once the equilbrium point is set, an invariant characteristic curve is established, and movement occurs to bring the muscle into the new equilbrium point. The trajectory of the limb follows an invariant path that brings the limb quickly into equilibrium, and no specific dynamics computation is made then by the CNS. An advantage of this method of control is that the muscles-as-springs automatically generate restoring forces to keep the arm on a specified virtual trajectory when small perturbations occur, avoiding the need for an active feedback controller to correct small errors. The issue of motor equivalence is simplified, as is the degrees of freedom problem, and variability, since speed is controlled independently of resting length.

For the mass-spring model, a controller is not needed for generating joint torques over time (Step 3 in Figure 5.3) because they can be generated by properties of the muscles themselves. The controller changes the virtual position of the arm (i.e., the equilibrium point between agonist/antagonist muscles) by adjusting some control parameter. Feldman (1986) argued that the resting length threshold between agonist/antagonist is selected as the control variable. In contrast, Bizzi (1980) argued that the equilibrium point is controlled by setting the alpha motoneuron activity to the agonist/antagonist muscles. There is evidence for both. For example, Bizzi, Dev, Morasso and Polit (1978), trained primates to perform pointing tasks. After training, they were deafferented. Under conditions where unknown loads were added to the arm, there was consistent over or under shooting. When the load was removed, the correct position was attained.

In summary, kinematic transformations have been observed in behavioral data that suggests that the CNS uses linear approximations for performing the transformation. There is little variability in the angular motion between the shoulder and elbow joints (Soechting & Lacquaniti, 1981). A directional population vector has been observed

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[8]A system is in equilibrium when there are no net forces and torques acting on it.

in the motor cortex, providing evidence that the motor cortex may be viewed as a computational map. At the same time, some features of limb movements may not be explicitly planned by supraspinal systems. It is possible that the CNS is using simplifying rules to generate close but inexact approximations (or ballparks) of an intended movment. The hand path, for example, which tends to be in straight lines and exhibit bell-shaped velocity profiles, may not be being planned, but may emerge as a result of the CNS transformations from goal location to intrinsic joint angles or muscle lengths and/or from the mechanical properties of the limb.

5.3.2 Symmetric vs asymmetric velocity profiles

A pointing study performed by Atkeson and Hollerbach (1985) brought out important features about unrestrained arm movements. Subjects started with their hand in one of six locations in space, and were asked to move their arm within a plane to another location which was lit with a light-emitting diode. In order to collect these data, Atkeson and Hollerbach used a SELSPOT system, allowing them to track the subject's index finger tip, wrist, elbow, and shoulder movements over time. Small, light-emitting diodes were attached to the body part to be tracked, and solid state cameras captured the kinematics of the movement. In terms of the path of the wrist, some paths were straight-line, some were curved, depending on the location of the movement in the workspace. Subjects were required to carry a load in their hands for some of the trials. For a given direction, there was path invariance with speed and load. Atkeson and Hollerbach found that practice did not influence the movements. They showed that the tangential velocity profile, scaled both in time and amplitude, was invariant for all subjects, speeds, loads and directions (shown in Figure 5.4).

Other investigators have not always found symmetric velocity profiles in pointing tasks. MacKenzie, Marteniuk, Dugas, Liske, and Eickmeier (1987) replicated the conditions from Paul Fitts' study on discrete aiming (Fitts 1954, Experiment 2), and found systematic effects of target size on the degree of asymmetry in the tangential velocity profiles. Subjects were asked to point with a stylus 'as quickly and as accurately as possible' to a target of varying size and at varying distances. The question being asked concerned whether there was a reliable kinematic measure of the precision requirements of the task. In this case, Fitts' Law (Fitts, 1954) was used, which states

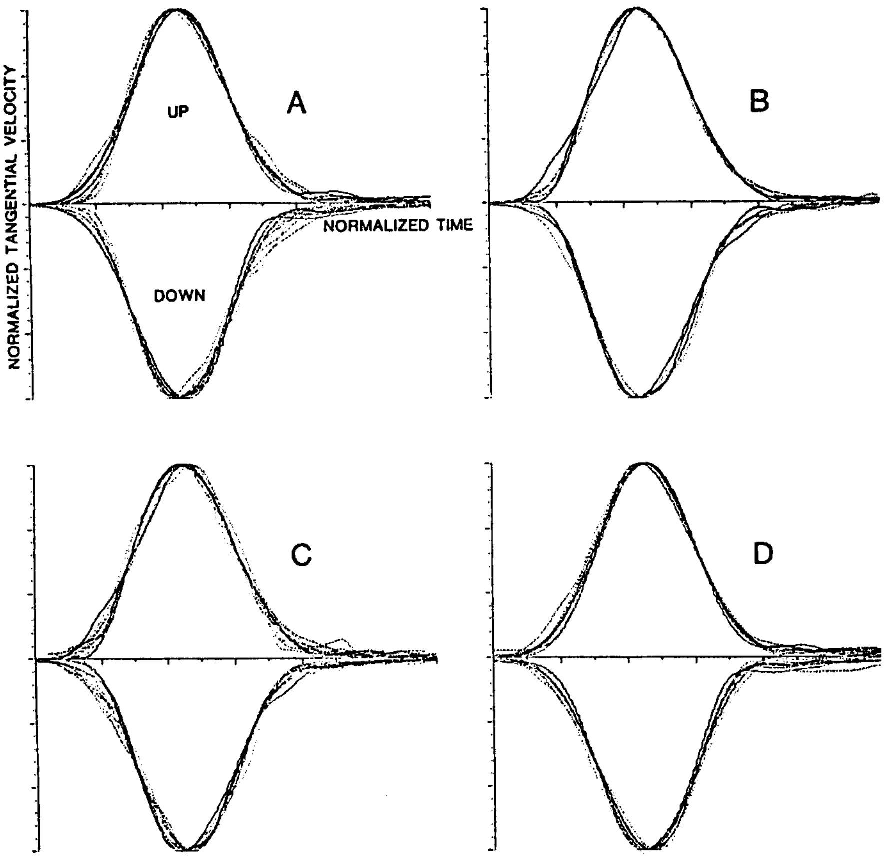

Figure 5.4. Wrist tangential velocity profile shape invariance across a) different speeds b) different loads, c) different movements, and d) different subjects (from Atkeson and Hollerbach, 1985; reprinted by permission).

that movement time (MT) is directly proportional to the index of difficulty (ID) of the task:

$$MT = a + b \times ID \tag{2}$$

where:

$$ID = \log_2(2A/W) \tag{3}$$

The amplitude of movement, A, is an extrinsic object property and the width of the target or target tolerance, W, is an intrinsic object property. Using a WATSMART system (Northern Digital, Waterloo), MacKenzie et al. (1987) measured the MT of the tip of the stylus, its time to peak resultant velocity, and the percentage of movement time after peak resultant velocity. When plotting MT against ID, a linear relationship is seen, replicating Fitts' Law. There was a differential effect of target size and amplitude on these parameters. As seen in Figure 5.5a, in plotting ID vs the time before the peak resultant velocity (the acceleration time or phase), there was a noticeable effect of amplitude. For each target size, the acceleration time increased as the ID increased (primarily due to amplitude). For each amplitude, there was no effect of target size on the acceleration time. In Figure 5.5b, the data are normalized in order to examine the percentage of MT after peak resultant velocity (the deceleration phase). For each amplitude, this measure increased as the ID increased. That is, as the diameter of the targets became smaller, the percent of time spent in the deceleration phase of the movement increased. The value of peak velocity was scaled to the amplitude of movement; i.e., as the amplitude of movement increased, so did the value of peak velocity, although the relative timing of acceleration and deceleration components of the movement remained invariant for a given target size.

These results indicate that the resultant velocity profile is not symmetrical. Fitts' Law states that the MT will increase as the target size decreases; here, it can be seen that the reason that the MT increases is because of a relatively longer deceleration phase for smaller target diameters. The results show that the time spent in the deceleration phase was predicted by ID as well or better than MT. This was not the case for acceleration time. Only movement amplitude affected the time to peak velocity. Thus, amplitude and target size effects were disassociable in that the shape of the tangential velocity profile was a function of target size (accuracy), and the peak speed along the path of the trajectories was scaled according to movement amplitude.

MacKenzie et al. (1987) found a systematic lengthening of the deceleration phase of the tangential velocity profile with decreases in target size, and operationally defined a lengthening of the deceleration phase as a 'precision effect'. In contrasting our asymmetric velocity profiles with the shape invariance identified earlier by Atkeson and Hollerbach (1985), we noted that their subjects made unrestrained pointing movements in the dark without making contact with target surfaces. With full vision and room illumination, our subjects contacted target plates; our findings showed that impact velocity at

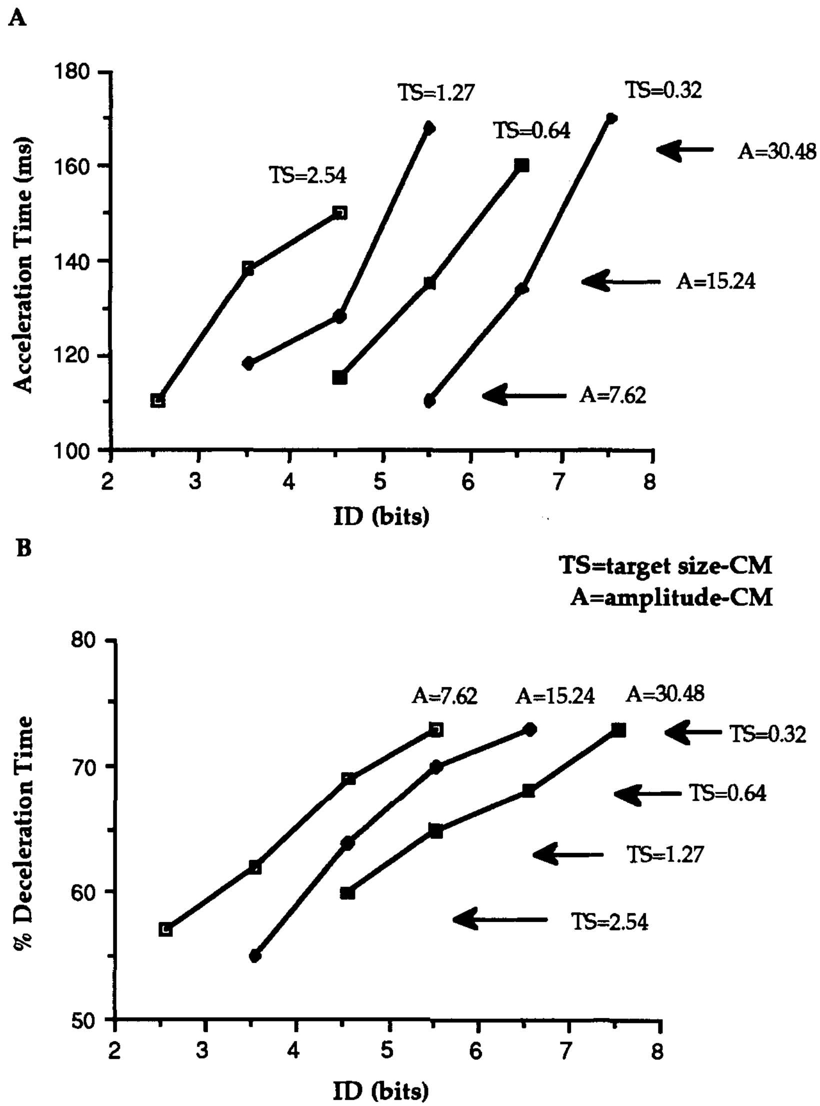

Figure 5.5: **A. Acceleration time (ms) as a function of ID, for each of the target sizes. Time to peak speed was primarily a function of amplitude, not target size. B. Percentage of MT spent in deceleration as a function of ID, for each of the amplitudes. More time was spent in the deceleration phase as target size decreased. Amplitude had no significant effect on the deceleration phase of the movement (from MacKenzie et al., 1987; *adapted by permission*).**

target contact increased with target size. Worringham (1987) showed that impact forces also increase linearly with target size.

The above findings suggest that the target surface was used to decelerate the limb. MacKenzie (1992) examined the effects of target surface and pointing implement on 3D kinematics in a Fitts' aiming task. Conditions for Index of Difficulty (ID) included: 2 amplitudes (30, 40 cm) and 4 target diameters (1, 2, 4, 8 cm). These were factorially combined with 2 implements (index finger tip or pen tip) and 2 target types (hole or solid target). Eight adults made discrete midline aiming movements to vertically placed targets. On each trial, subjects placed the pointer in a constant start position. After a 'ready' prompt for preparation, on a 'go' signal subjects moved as quickly and accurately as possible to the target. The OPTOTRAK system (Northern Digital, Waterloo) collected 3D coordinates of position of the implement tip at 200 Hz. MT results replicated Fitts' Law. Kinematic differences among the pointing implement and target surface conditions showed: the pen was faster (518 ms), with greater, earlier peak kinematic values than the finger tip (550 ms); subjects had lower peak kinematic values and a greater proportion of time decelerating to the hole target (70%, 408 ms) than the solid target (64%, 310 ms). Thus it appears that, in addition to the precision effects of target size, the target surface was used to decelerate the aiming movement, since subjects spent a longer proportion of time in the deceleration phase when aiming to the hole. This demonstrates that humans can take advantage of contact forces in interaction with objects, and the importance of subject initiated deceleration control when decelerative forces due to impact are not available (see also Milner & Ijaz, 1990; Teasdale & Schmidt, 1991).

Bullock and Grossberg (1986, 1988, 1989) developed a model that produced both symmetric and asymmetric velocity profiles. The Vector Integration to Endpoint model, VITE, (see Figure 5.6) produces arm trajectories from a target position (Step 1'). A target position command, T, contains desired muscle lengths for all trajectory-controlling muscles. An internal model of the muscle's present length, P, is maintained. The arm trajectory basically tracks the evolving state of the P. A difference vector, V, is computed between the desired and current muscle lengths. A time-varying GO signal, G, gates V to the internal model, which in turn integrates V through time. The size of the GO signal determines the speed at which the limb will move. The difference vector is updated as follows:

$$\frac{d}{dt}V_i = \alpha(-V_i+T_i-P_i) \tag{4}$$

where α is a positive constant. The present position command is updated as follows:

$$\frac{d}{dt}P_i = G[V_i]^+ \tag{5}$$

where $G[V_i]^+ = \max(V_i,0)$. Motor priming is possible with this model, because a new target may be specified, but no movement will occur until the GO signal increases above zero. The difference vector can still be computed.

Grossberg and Bullock showed how the VITE[9] model can generate asymmetric velocity profiles across different movement durations. This is elaborated in Figure 5.7. The GO signal controls the speed of the movement. In Figure 5.7a, an asymmetrical velocity profile is seen for a slow movement. As the movement speed increases (Figures 5.7b and c), the velocity profiles become more symmetrical. This is seen in Figure 5.7d, where these velocity profiles are superimposed. Evidence in the neurophysiological data for the V signal has been seen in the directional population vector of Georgopoulos and colleagues (Georgopoulos et al., 1988; Kettner et al., 1988; Schwartz et al., 1988). The VITE model is consistent with higher peak velocity in target switching experiments. When there is an internal model of target location and current hand position, error corrections don't need to be made based on proprioception. The VITE model can generate different offsets for muscles, as a function of the GO signal, thus staggering the contraction onset times. Trajectories are generalized in joint space. Motor commands to a muscle group are read out at staggered times after the GO signal is received. While it can reach the same goal from arbitrary initial states at variable rates, the model cannot be easily applied to multi-joint movements and does not address learning.

In summary, point to point simple arm movements have predictable spatial paths, although whether or not they are curved depends on where in the workspace the movement occurs. For unrestrained

[9]Grossberg and Kuperstein (1986, 1989) have developed a feedback model (the muscle linearization model MLN) that compares the feedforward internal model (P in Figure 5.6) to sensory feedback. Mismatches between these generate error signals which alter the gain of the motor command adaptively.

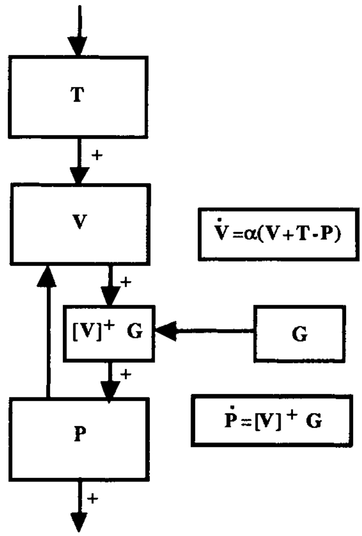

Figure 5.6 Vector Integration to Endpoint model for generating arm trajectories. The difference V between the desired muscle length, T, and a model of the present muscle length, P, is computed. On receiving the go signal, G, V is gated to the internal model, integrating V through time. The arm follows the evolving state of P (from Bullock & Grossberg, 1989; reprinted by permission).

pointing movements, there is little variability within and between subjects. There is little variability in the spatial path taken by the wrist. The path is independent of speed, and inertial loads. Velocity profiles tend to be bell-shaped, and superimposable when scaled in time or amplitude, indicating perhaps a 'ballistic' controller driving the arm without regard to sensory feedback. In general, goal-directed movements have one accelerating phase and one decelerating phase if their trajectory is approximately along a straight line. Asymmetries in tangential velocity profiles may reflect the 'precision demands' of the task, that is, the time spent in the deceleration phase of the movement. For pointing tasks requiring more accuracy, movement time increases and the velocity profile becomes more asymmetrical, with a longer deceleration tail. As well, longer deceleration phases are associated with self-generated decelerations, when individuals are unable to use decelerative impact forces. Speed and accuracy are defined in a relationship knows as Fitts' Law which states that movement time is directly pro-

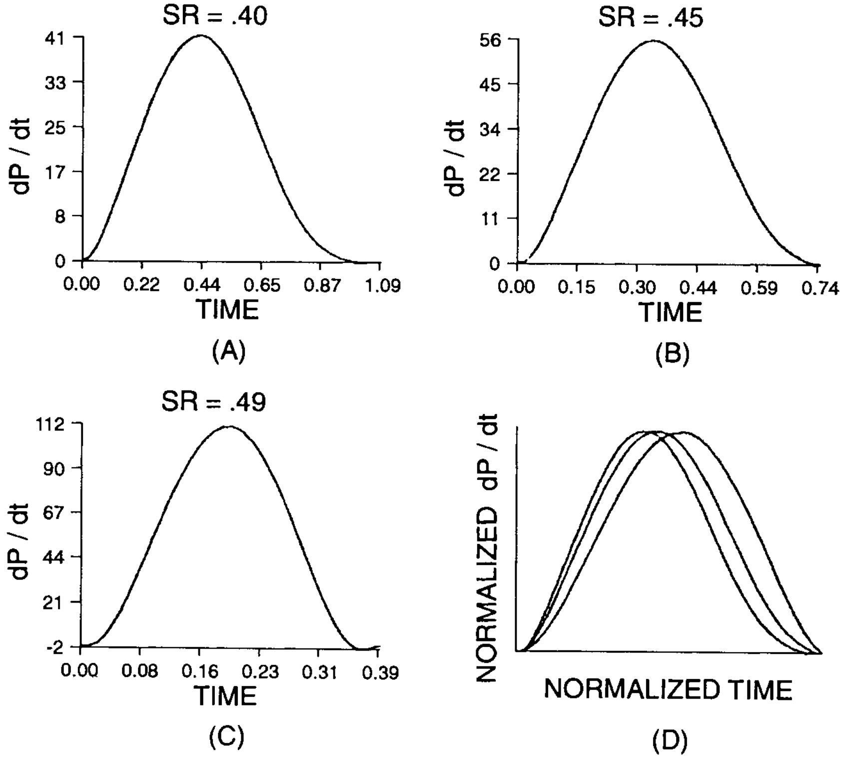

Figure 5.7 Velocity profiles from the VITE model. A. Velocity profile of 20 unit distance movement with small GO signal. B. Velocity profile of 20 unit distance movement with medium GO signal. C. Velocity profile of 20 unit distance movement with large GO signal. D. Superimposing velocity profiles from A, B, and C. Note slower movements have an aymmetrical velocity profile. SR=time taken to move half the distance divided by total movement time (from Bullock and Grossberg, 1989; reprinted by permission).

portional to a function of movement amplitude and target width. The coordination of all muscles involved in a multi-joint movement reflects a rather stereotyped behaviour, with coupling synergy of the shoulder and elbow during reaching. Plamondon (1992) provides a sequential generation model to explain the origin of asymmetric bell-shaped velocity profiles and to describe them with a log-normal function. Neural simulations that produce symmetric and asymmetric velocity profiles can be constructed to generate a muscle length, given a desired speed and muscle length, using a difference vector. Excellent reviews of pointing, aiming and the role of vision are provided in Meyer et al. (1990) and Proteau and Elliott (1992).

5.3.3 Generating joint level trajectories

Jordan (1988) used a recurrent artificial neural network[10] to generate joint angles from one or more desired hand locations in a body coordinate frame (Step 2 in Figure 5.3). A goal location was specified in a two dimensional space, as seen in the inset to Figure 5.8 where two goal locations are shown. Jordan simulated a non-anthropomorphic manipulator with six degrees of freedom: two translational (in the x and y directions) and four revolute joints[11]. As seen below, any other configuration of joints could have been used, modelling an anthropomorphic arm or even a finger or two.

The neural network architecture is seen in Figure 5.8. In the bottom half of the figure, six input units, here called plan units, encode a sequence of goal locations. This sequence of goal locations is translated into a sequence of joint angles at the articulatory layer (one unit for each joint controller or manipulator degree of freedom). Two target units specify the Cartesian coordinates of the end point of the arm. For a given arm configuration, as specified by the six articulatory units, the Model Network determines the end point of the arm. Jordan added two units (here called state units) to create recurrent connections from the target units back into the network, thus allowing time-varying sequences of configurations to be computed (in the Sequential Network).

Jordan's algorithm involves two phases of computations. During the training phase, the system learns the forward kinematics using the Model Network (top half of the figure). As a training set, random static configurations are presented to the articulatory layer. The actual end point of the manipulator is computed by summing up weighted activation values of the articulatory units and then the weighted activation values on the hidden layer. This computed endpoint is then compared to the desired location of the end point. If there is a difference, the generalized delta rule is used to change the weights between the articulatory units, hidden layer, and target units in order to

[10]For a more detailed discussion of artificial neural networks, see Appendix C.

[11]A revolute joint is like the hinge joint of the elbow.

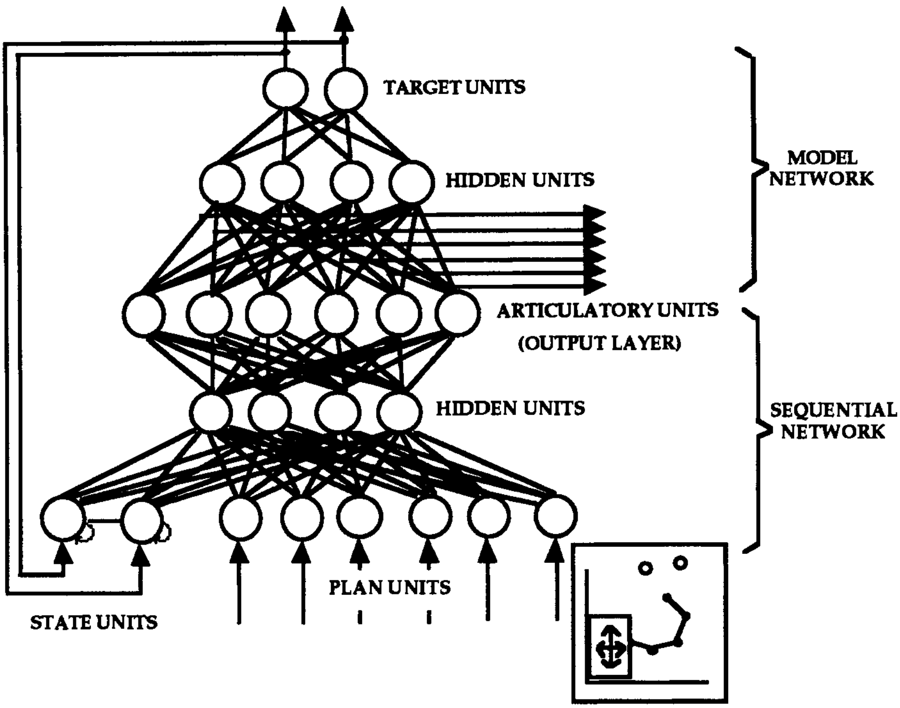

Figure 5.8. Jordan's network for computing inverse kinematics of a sequence of actions. It consists of two networks. The upper one, the Model Network, computes the forward kinematics for the manipulator. The lower one, the Sequential Network, computes the trajectory in joint space that will bring the endpoint of the manipulator to the desired hand space locations. In the inset, the six degree of freedom manipulator is seen, consisting of two translational degrees of freedom and four rotational ones (from Jordan, 1988; adapted by permission).

reduce this difference. Computing the forward kinematics in this manner took about 2000 times of repeated trials, converging on a solution when the difference, or error, between the desired and actual endpoint was reduced to almost zero.

During the second phase, the sequence of kinematic configurations is learned using the Sequential Network (bottom half of the figure). The state units are initialized to a time step of 0. A plan (a sequence of goal locations) is presented to the plan units. For a given time step, a joint configuration is computed in a method similar to that described above. A training set is presented and joint angles computed for the current weights. Using the Model Network, a manipulator end point is computed for this joint configuration (the weights in the Model Network stay fixed during this second phase). The computed end point location is compared to the desired goal location, and if there is a difference, the weights in the Sequence Network are modified, again using the generalized delta rule. This sequence learning phase took 77 cycles to find a solution for a sequence that involved touching four goal locations in a counterclockwise order. By shifting the second goal and asking the manipulator to perform the task again, only 5 trials were needed.

Learning using the generalized delta rule involves updating the weights by subtracting the actual output from the desired output and adjusting the weights so that the error between the two will be reduced. Jordan added intelligence, so that weights are adjusted according to various rules and constraints. If the result of the computation satisfies the constraint, the normal error propagation is performed; if the constraints are not met, the weight is not changed. Jordan used two types of constraints. Configurational constraints defined regions in which an output vector must lie. These included don't care conditions, inequalities and ranges, linear constraints, nonlinear constraints, and other optimality criteria. If it doesn't matter that an error exists, the weight is not changed. With inequality constraints, the weight was changed only when a specific inequality existed between the computed value and the desired value, for example, the computed value is larger than the desired value. Range constraints were used when the error could lie within a defined range of two values. Linear constraints added two or more units in a linear fashion, apportioning the error between them. Temporal constraints defined relationships between outputs produced at different times. Whereas configurational constraints arise from structural relations in the manipulator and/or the environment, temporal constraints arise from dynamical properties of the system. An important one is a smoothness constraint which allowed configuration choices to be made in the context of the arm's location. For this, units in the Sequential Network stored their activation value at the previous time step so that inverse kinematic solutions for points nearby in time differed minimally.

As mentioned, a problem with inverse computations is that there are non-unique solutions. Jordan turns this problem into a feature by using these constraints to maintain multiple inverse kinematic solutions. In Figure 5.9a, the network has learned a sequence of four

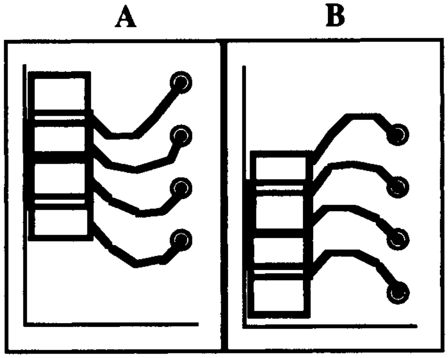

Figure 5.9. Six degree of freedom manipulator having learned two different sequences of four goal locations. Some of the goals in A and B are in the same Cartesian location. The network was able to choose different inverse kinematic solutions, using temporal constraints to provide a context for the decision. (from Jordan, 1988; reprinted by permission).

goals. Figure 5.9b shows another learned sequence which has two goal locations in common with the sequence in Figure 5.9a. However, even though the two target points are the same, the network generates different joint configurations. These configurations depend upon the temporal context in which the target point was embedded. Since the arm was bent upwards at the elbow in Figure 5.9b, the configuration chosen is a smooth transition from the previous one.

Jordan's model solves the inverse kinematic problem of generating joint angles from a goal location, addressing the underdetermined aspect of the problem. Using an adaptive constraint network that incorporates constraints at relevant levels, he offers a solution to motor equivalence problems (see Jordan 1989 or 1990 for further elaboration of these ideas). For configurational constraints that depend more on the structural properties of a particular manipulator, single unit and multiple unit constraints are maintained locally, acting as small filters to focus error-reducing adaptation. For temporal constraints that allow adaptation to occur within a historical context of the way nearby joints are changing, the error-reducing algorithm acts with knowledge of the previous state. While an intriguing model for trajectory learning, the question remains, how does the system learn the constraints in the first place? These had to be placed by Jordan himself. An interesting enhancement of the model would be for the system to learn the constraints in the workplace.

5.3.4 Generating muscle level commands

Using Jordan's Sequential Network, Massone and Bizzi (1989) drove a planar three-joint manipulator at the muscle level instead of at the joint level. The manipulator has four pairs of antagonist muscles: shoulder flexor and extensor, double joint flexor and extensor, elbow flexor and extensor, and the wrist flexor and extensor. As seen in the bottom of Figure 5.10, the plan units are simplified sensory views of the world in a shoulder-centered reference frame (centered in the same workspace as the manipulator). Each plan unit has a receptive field that covers nine pixels of the 15 x 15 pixel body coordinate frame. The activation of each plan unit is the sum of the pixel values within its receptive field. The advantage of this type of coding, called coarse coding, is that the network can generalize better and learn faster (Hinton, McClelland, & Rumelhart, 1986). The output units represent 'motor neurons', each unit controls one of the eight muscles. Thus the computation being performed here is Step 1', computing a trajectory in body coordinates from a goal location.

Using the generalized delta rule, Massone and Bizzi trained the network to generate a trajectory of muscle activations from a goal location. This inverse problem uses the mass-spring model so that the arm trajectory is generated following the virtual trajectory of equilibrium configurations defined by the elastic properties of muscles. However, it is still an ill-posed problem, and a cost function is needed to determine a unique solution. Massone and Bizzi used a minimum potential-energy cost function as their criterion, so that when the system of muscles is perturbed by an external force, the manipulator settles into a configuration of minimum potential energy, thus computing muscle activations for a given x,y goal location of the endpoint. The velocity is constrained by a bell-shaped velocity profile. The output is a set of eight-dimensional vectors of muscle activations, each vector corresponding to an equilibrium position.

In simulations of the learning phase, various endpoint trajectories, six time steps in length covering the workspace, were presented to the network. Using the minimum potential energy criteria for generating arm configurations, the network produced straight-line movements and bell-shaped velocity profiles, and was even able to generalize joint reversals, as seen in Figure 5.11.

In analyzing the weights produced on the connections, Massone and Bizzi observed reciprocal inhibition between agonist-antagonist pairs and evidence of synergies between all hidden units. For example, positive correlations were found between flexors and extensors

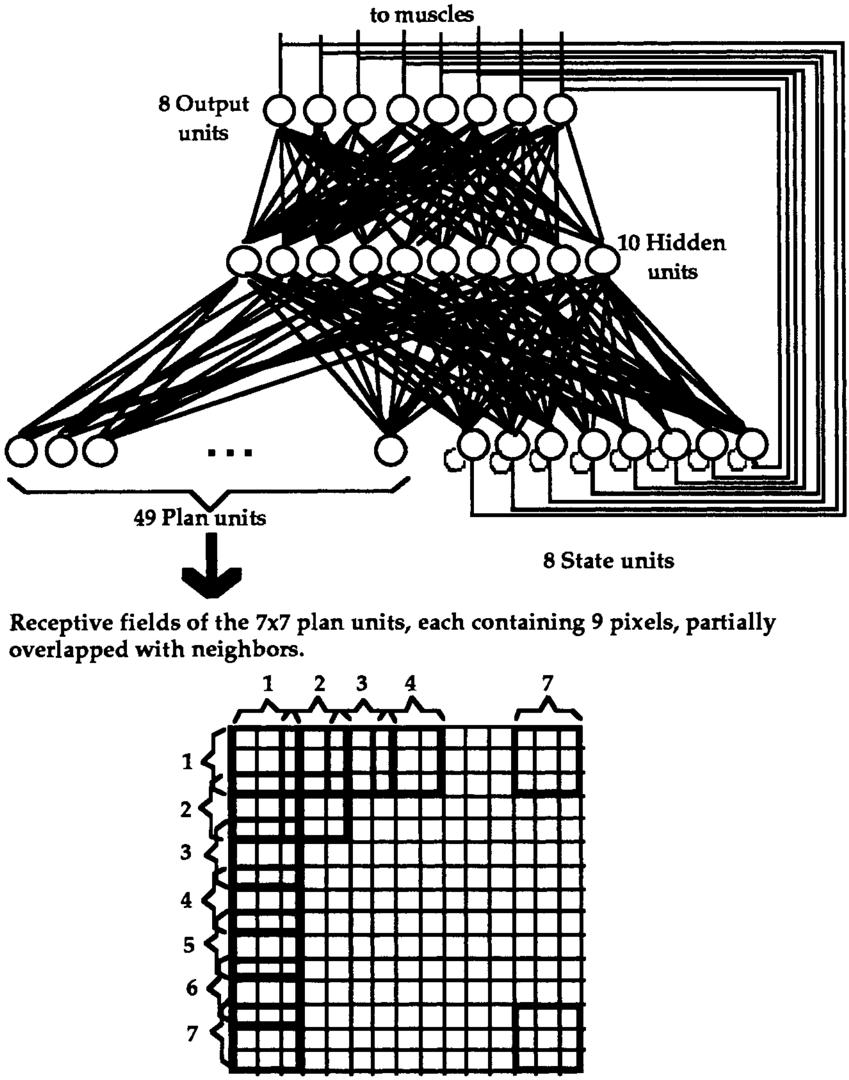

Figure 5.10 Massone and Bizzi's (1989) computational model used to compute hand trajectory and muscle activation over time. The network is the Jordan Sequential Network. Here, the input is represented by a highlighted location in a 15 x 15 grid. Input units, or plan units, coarsely code the sensory world, sampling a 3 x 3 space, and computing an average over that space. Output units to the muscles encode a sequence of a set of muscle activations.

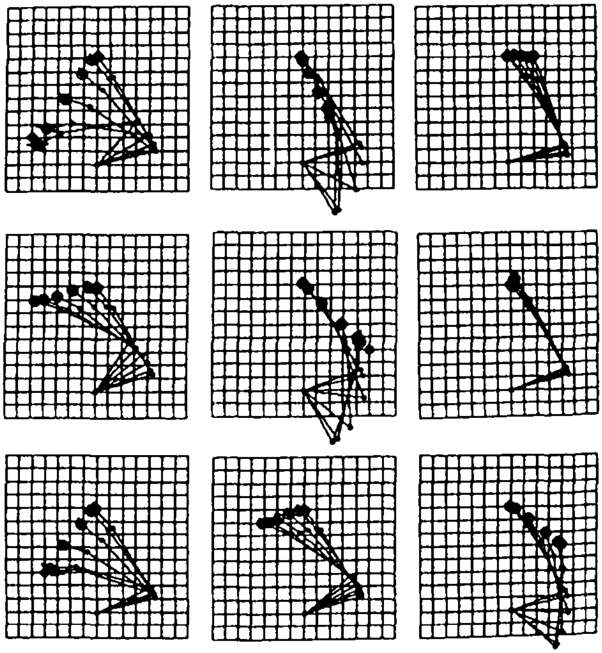

Figure 5.11. Generalization capability learned after 15 trajectories. The top-left trajectory contains a generalization of the joint reversal on the shoulder. The rightmost trajectory in the second row is a particular case of generalization in which the goal location was on the limb endpoint. Although the network was not explicity taught about the initial posture, it understood how the limb is positioned at the beginning of each trajectory (from Massone and Bizzi, 1989; reprinted by permission).

for some of the units, and between isolated pairs of flexors or between isolated pairs of extensors in other units.

An interesting experiment had to do with changing the target location after movement started, as seen in Figure 5.12. When the second target appeared after two time steps were made by the limb, the trajectory was generally straight; with three time steps, changes in the trajectories were seen. Because each point is an equilibrium point between the agonist-antagonists that had no history, the trajectories are not smooth. One solution is to use dynamics to make the output also a function of the past outputs.

The Massone and Bizzi model for muscle activation demonstrates a method for computing a hand and muscle-level trajectory from a goal (Step 1'). They use a muscle model and a cost function of minimum potential energy to compute the muscle activation given an endpoint goal location. Simplifications include bypassing a coordinate transformation by using the same coordinate frame for sensing and the spatial coordinates of the hand. In addition, eight muscles are controlled by only eight motor neurons in their model, while in reality there are thousands of motor neurons for these muscles. They do not explicitly compute the actual endpoint, because it is implicit through the muscle model; however explicit endpoint positioning is crucial at a planning level. Finally, they merge velocity and trajectory into one computation.

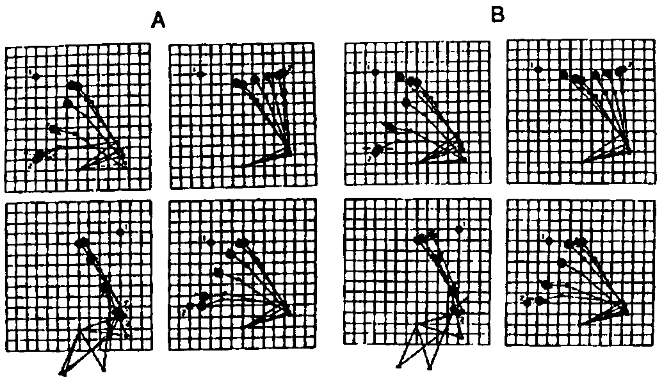

Figure 5.12. Double target experiment. (a) The first target was turned on for two time steps, and then it was turned off. (b) The first target was turned on for three time steps, and then turned off (from Massone and Bizzi, 1989; reprinted by permission).

5.3.5 Generating joint torques

Kawato, Furukawa, and Suzuki (1987) offered a hierarchical model of how this motor learning and control might be accomplished, as seen in Figure 5.13. As a model for generating motor torques from a desired trajectory expressed in body-centered coordinates, it computes Step 3 of Figure 5.3. The desired motor pattern, x_d, is sent from elsewhere in the brain to the motor cortex, where the motor command, u, is computed. In this case, the motor cortex would be computing the inverse dynamics, that is, computing the torque from

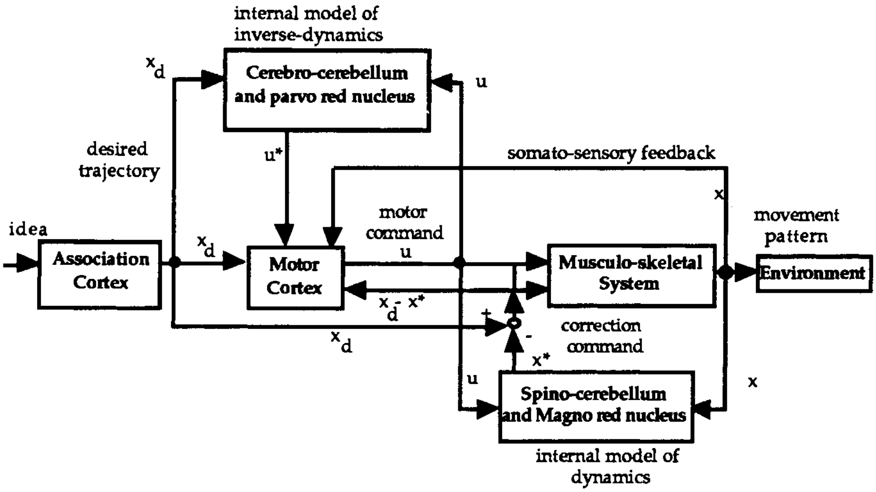

Figure 5.13. Hierarchical feedback-error learning model for control and for learning of voluntary movement. Somatosensory feedback x from the periphery is initially used by the motor cortex for adjusting the on-going motor command u. As the system learns the internal model of its dynamics, the transcortical corrections are replaced by a faster cerebellar feedback pathway that can more quickly adjust the motor command (using x*). Eventually, the system develops an internal model of the inverse dynamics, and can use an even faster, feedforward cerebellar pathway (generating u* to replace u) that can anticipate changes in the periphery (from Kawato, Furukawa & Suzuki, 1987; adapted by permission).

the trajectory. Because the input is the desired motor pattern, x_d, the output is a feedforward motor command. This motor command, in the form of muscle torques, is sent to the musculo-skeletal system which in turn produces some actual motor pattern, x. The results of the movement are received back at the motor cortex on the line labelled 'somatosensory feedback' (through the medial lemniscus system) and feedback control reduces the error in x_d-x. However, delays in this path can limit the usefulness of this control method.

Kawato et al.'s hierarchical feedback-error learning control model suggests that two cerebellar regions can participate in feedforward and feedback control using internal models of the limb's dynamics. Besides the feedback path described in the previous paragraph, the results of the movement are received in the spinocerebellum, a part of the cerebellum that has two somatotopically organized maps of the entire body and receives proprioceptive information from the joint capsules, muscle spindles, cutaneous receptors, and tendon organs. The spinocerebellum (sending output to the magnocellular red nucleus) receives commands from somatosensory and motor cortices. Receiving this efference copy of the intended motor command u and feedback about the evolving movement, it can regulate the periphery by making error-correcting compensations for small variations in loads and smooth out the physiological tremor. Kawato suggested that this system provides an approximated prediction, x*, of the actual movement, x, since it has access to the motor command itself. To do this, the Spinocerebellum/Magno red nucleus system has an internal neural model of the musculoskeletal system's forward dynamics. The predicted movements error, x_d-x*, is sent to motor cortex and to the muscles. Slowly as learning proceeds, this internal feedback pathway replaces the external feedback path for feedback control.

At the same time, Kawato et al. (1987) suggested another area of the cerebellum is involved in predicting the motor command using an inverse dynamical model. The cerebro-cerebellum (having its output to the parvocellular part of the red nucleus) monitors the desired motor pattern, x_d, and the motor command, u. There is neural evidence for this, since the cerebro-cerebellum has outputs to the thalamus and motor and premotor cortex, and has inputs from the pontine nuclei which relays information from cerebral cortical areas that include the somatosensory, motor, premotor and posterior parietal area. It has no inputs from the periphery, and the parvocellular part of the red nucleus does not contribute to the rubrospinal tract, meaning that it does not have a direct output to the musculo-skeletal system the way the magnocellular part does. Kawato et al. suggested that the cerebrocerebellum has an internal model of the system's inverse-dynamics, thus in effect modelling motor cortex. In simulating the inverse dynamics, Kawato et al. used a feedforward and feedback control model, such that:

$$T(t) = T_i(t) + T_f(t) \text{ or} \tag{5}$$

$$u = u^* + Kx \tag{6}$$

where T(t) is the total torque at time t, $T_i(t)$ is the torque computed by the inverse-dynamics model, and $T_f(t)$ is the feedback torque. The Cerebrocerebellum/Parvo Red Nucleus computes a motor command u* from the desired trajectory x_d, sending its results to the motor cortex.

The goal of this neural model is that the Cerebrocerebellum/Parvo Red Nucleus slowly takes over the work of the motor cortex and the Spinocerebellum/Magno Red Nucleus by being able to accurately predict the motor command using its inverse-dynamics model. If the inverse-dynamics model is an accurate model of the system, then the feedback torque will be zero, thus removing movement errors. However, in order to accomplish this, the inverse-dynamics model must be learned, and taught by the teaching signal, which here is the total torque, u. When the actual trajectory differs from the desired trajectory, feedback torque occurs. This becomes an error signal. Reducing the error by updating its internal model, the inverse-dynamics controller slowly replaces the internal feedback with the feedforward model. The advantage of this approach is that the model learns the dynamics and inverse-dynamics of the system instead of a specific motor command for a specific movement pattern.

Feedback control, whether performed by the motor cortex on the external feedback, or else by the dynamics model controller using internal feedback, is limited in time. With the inverse-dynamics model, feedback torque is slowly replaced with feedforward torque, which anticipates the torque for the desired trajectory. Thus, the system is controlled faster. A problem with this approach is the amount of storage needed for the internal model. In Kawato et al.'s simulation of a neural net for a three-degree-of-freedom manipulator, 26 terms were used in the internal model's non-linear transformations. For a 6 degree of freedom manipulator, 900 would be needed. For an arm having 11 degrees of freedom and 33 muscles, the number of terms is astronomical. The authors argued that these can be learned by the synaptic plasticity of Purkinje cells, which are large neurons in the cerebellum. Another question relates to generalizing experiences obtained during learning and whether what's learned can be used for quite different movements. Kawato et al. say that their method does not require an accurate model or parameter estimation.

5.4 Arm and Hand Together, To Grasp

While the behavior of the arm in aiming and pointing tasks is a first step towards understanding sensorimotor integration and motor control, reaching to grasp an object brings the additional complexity of posturing the hand appropriately for impending interactions with the environment. In grasping, the hand must apply functionally effective forces, consistent with perceived object properties for a given task. Creating a stable grasp means taking into account active forces and torques as well as passive ones. In order to use an opposition space after contact with the object, the reaching and grasping schemas in the CCP must be activated and receive the necessary information, in order to set up an opposition space[12]. The planning process entailed 'seeing the opposition vector' in the object, appropriate for the task at hand, and selecting the opposition space parameters including: the type of opposition; the virtual finger mapping; and the virtual finger state variables when in contact with the object at stable grasp. After planning, the fundamental problem for setting up an opposition space (the motor control system from movement initiation to contact) is through coordinate transformations, to configure the hand and arm for placement on the object, consistent with the above opposition space parameters. Reminiscent of Jeannerod's discussion of superimposing 'proprioceptive maps' and 'visual maps', the subgoal for setting up an opposition space is to align the hand configuration with the opposition vector seen in the object, satisfying the opposition space parameters. Thus, for grasping, the opposition vector drives the movement execution prior to contact.

What is known about reaching and grasping and the relationship between the two schemas in Figure 5.1? With regard to the transport and grasping components, Jeannerod (1981, 1984) placed markers on the distal parts of the index finger and thumb and found systematic differences in the effects of object properties on reaching and grasping. He contrasted conditions in which subjects grasped small or large objects, with conditions in which subjects had to move to different amplitudes in the sagittal plane. Analyses of the kinematics of the hand transport were combined with aperture between the two markers to infer central control. As seen in Figure 5.14, distance of the object away from the subject affected the transport component (peak velocity increased with the distance to be moved) but not the grasping component. Conversely, object size affected the grasping component (maximum aperture was bigger for a larger object), not the transport component. Jeannerod made an important distinction between <u>intrinsic object properties</u> and <u>extrinsic object properties</u>[13]. He suggested

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[12]Opposition space terminology was introduced in Chapter 2, where we defined the concepts of opposition space and virtual fingers. Virtual finger orientation is a state variable, and the finger position constraint corresponds to the opposition vector's magnitude. In Chapter 4, we made explicit the notion that subjects "see the opposition vector" in the object, in the spirit of action oriented perception.

[13]Introduced in Chapter 3, Jeannerod distinguished <u>intrinsic object properties</u> (identity constituents such as size, and shape) from <u>extrinsic object properties</u> (or

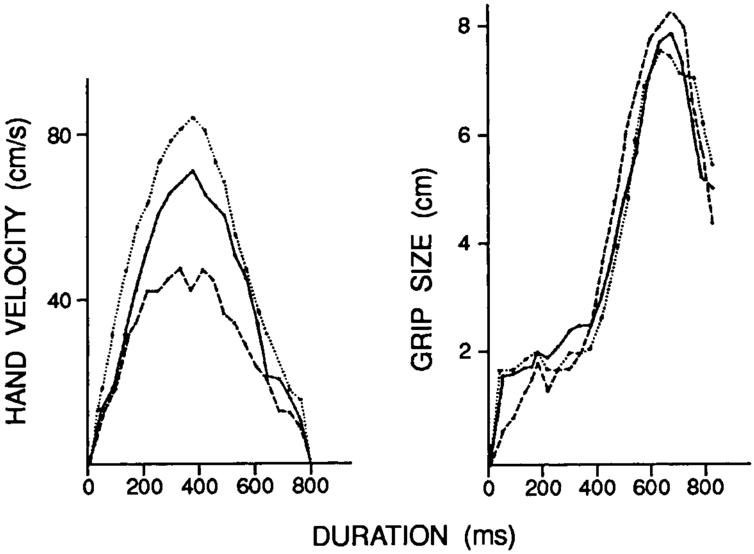

Figure 5.14 **Wrist velocity and aperture profiles for grasping a large cylinder 5.5 cm in diameter, without vision of the object. On the left, the velocity profile is shown as the subject reaches out to grasp an object of constant size placed 25, 32 or 40 cm away. On the right, no difference is seen in the pattern of aperture between the thumb and index finger over the course of the movements, among the distances evaluated (from Jeannerod, 1984; reprinted by permission).**

that the two types of properties are likely to be detected through different structures or channels. Specifically, for grasping an object, separate visuomotor channels are activated in parallel by a specific visual input and controlling a specific part of the limb musculature. For example, extrinsic spatial properties of an object activate proximal muscles (e.g., about the shoulder joint) for the transport component, and intrinsic object properties activate distal segments (e.g., wrist and fingers) for the grasping component.

With respect to the coordination between reaching and grasping, he found that in the descent period after peak velocity, a change in the velocity was seen at around 70-80% of the total movement, which cor-

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egocentric spatial properties such as distance, orientation, direction and velocity of object motion with respect to the body).

related with the beginning of finger closure. This correlation between the time of peak deceleration of the wrist and the time of peak aperture of the grip led Jeannerod to hypothesize a central program or pattern for the coordination of a unitary act, and that reaching and grasping movements can be separated into two phases. These are an initial, faster arm movement during which the fingers preshape, and a slower arm movement beginning after peak aperture, during which the fingers capture the object. During the slow second phase, Jeannerod noted many corrective type movements. He argued that the arm (the transport component) is controlled separately from the hand (the grasping component), but that these are temporally linked for the coordination of prehensile movement.

In the Jeannerod experiments, some reaches had no visual feedback, while others were performed in such a way that the object could be seen but not the arm and hand as the reaching occurred. It is interesting to note that the low velocity phase was still observed in the absence of visual feedback. This would suggest that the low velocity phase is not reflecting only the visual corrections as the hand gets closer to the object. However, in studies where the subject's gaze was monitored, visual information is sought after, if available. The kinematics during this second phase are affected by the type and amount of visual information available, by the type of posture, and by the object size. Jeannerod (1984) explained that movements having no visual feedback often fell short of the target by 1-2 mm. Movements under visual control were longer in duration.

In examining the behavior of reaching to grasp an object, we focus in this section on different aspects of the kinematic profiles[14]. Some of these have been discussed previously. We can examine the nature of the velocity or acceleration functions, looking at kinematic landmarks like peaks and their times of occurrence. If the profiles are normalized in time or amplitude, we can evaluate whether or not they come from the same family, as we did with the arm pointing and aim-

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14 Jeannerod's seminal work (1981, 1984) was performed using cinematography, at 50 frames/s. The introduction of computerized motion analysis technologies in the 1980s and 1990s has changed dramatically the possibilities, nature and scope of kinematic analyses of natural human movements like grasping. Prior to this time, a 2D or 3D view obtained from film required manual digitizing of body segments. With the advent of computer-based optoelectric, video and sonic systems, the time consuming and tedious process of manual digitizing was eliminated and 3D kinematics were obtainable at higher sampling rates than required (e.g., 200 Hz). However, new challenges concerned procedures for data management and analysis.

ing velocity profiles. One approach is to look for kinematic invariances. Referring to Figure 5.14, Jeannerod (1984) showed that peak grip aperture remained invariant with changes in movement distance. In contrast we note systematic variation in that the value of peak hand velocity increases with movement distance (confirmed through inferential statistics as more than one might expect to find due to random variation alone).

For the transport component, the velocity profile is roughly bell-shaped, and in this case symmetrical, i.e., about the same proportion of time is spent in the acceleration phase prior to peak tangential velocity, as in the deceleration phase after peak velocity. We would say that the velocity profile for transport was scaled to movement distance, if for the three distances, the shape of the velocity profile was similar when normalized in time, and only the amplitude varied. In this case, normalizing in the amplitude domain would lead to superimposed velocity profiles. Differentiating the resultant velocity profile to examine the rate of change of speed along the path of the movement, we could similarly address the acceleration-time function, noting the amplitude and timing of peak acceleration, zero crossing (corresponding to peak velocity), and peak deceleration. Lack of smoothness in the deceleration phase of the movement, local peaks and valleys, or multiple zero crossings in the acceleration function might indicate corrections to movement or changes in the plane of movement. Insight might be gained from examination of the phase planes, e.g., some variable plotted against its derivative. The spatial path reveals another view of the motion pattern of the hand. The variability of all the above variables over trials and experimental manipulations can be analyzed to reveal underlying planning and control processes (for a review, see Marteniuk & MacKenzie, 1990).

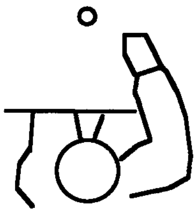
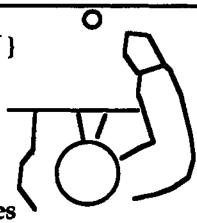
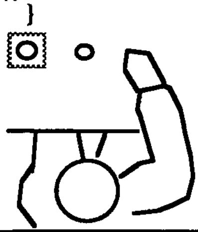
With respect to the grasp component, one metric that researchers have used in studying pad opposition or precision grasping has been the separation between the thumb and index finger pads. Jeannerod (1981, 1984) found that the grip aperture between the thumb pad and index finger pad increases until it reaches some peak separation, and then the fingers close in around the object until contact is achieved (see Figure 5.14). This is a highly stereotypic pattern, the preshaping prior to and the enclosing after maximum aperture. The peak aperture, the time spent in preshaping and enclosing, as well the rate of hand opening (finger extension) and rate of enclosing are all potentially valuable dependent measures to understand control of the movement prior to contact. Note the relativity and power of grip aperture as an explanatory dependent measure. In pad opposition, when the fingers contact the object this opening must correspond to the length of the opposition vector; in addition, the fingerpads must be aligned along the orientation of the opposition vector. As we will see, the grip aperture may be a higher order control variable.

Considering the black box introduced in Figure 1.2, we can consider all these kinematic measures of prehensile behavior as outputs. We saw grasp types and opposition space parameters and outputs in Chapter 2. Jeannerod introduced the important distinction between intrinsic and extrinsic object properties accessible through vision; he also addressed the issue of the role of visual information. In the following sections, we consider what has been learned about object properties and task requirements, and the roles of sensory information, through research analyzing the kinematics of movements, primarily using pad opposition (or precision grip), but also using palm opposition (or power grasp).

5.4.1 Task requirements and object properties

Further exploring the kinematics of grasping and aiming tasks, Marteniuk, MacKenzie, Jeannerod, Athenes, and Dugas (1987) varied precision requirements, showing how intention, context, and object properties affect timing parameters of prehensile movements. Table 5.1 summarizes the experimental conditions and results. In the first experiment, they varied the goal, asking subjects to either point at or grasp medium sized disks. In the second experiment, they varied object fragility, by asking subjects to either grasp a light bulb or a tennis ball. In the third experiment, the subjects had to grasp a disk and either fit it carefully or throw it, thus varying the movement intent. Fitts' Law predicts that MT increases with the precision requirements of aiming or placing, but only addresses the effect of amplitude and target width on movement time. Marteniuk et al. (1987) bring in task influences (e.g., context, intent) as well as other object properties (e.g., fragility). In addition to movement time, Marteniuk et al. analyzed the velocity profile and separated the acceleration phase (before peak velocity) from the deceleration phase (after peak velocity). They observed (see Table 5.1) that the percentage of time in the deceleration phase was longer for grasping than pointing, for grasping the light bulb than grasping the tennis ball, and for fitting rather than throwing. In arguing that all these effects could be due to a 'task precision' requirement, they demonstrated that the increased MT is due to the disproportionately lengthened deceleration phase. Marteniuk et al. suggested that the duration of the deceleration phase

Table 5.1 Comparison of percentage of time in deceleration phase for three task choices. Note that as the precision requirements in the task increase, the percentage of time spent in the deceleration phase also increases. Data from Marteniuk et al. (1987).

	Task	W	A	% Time in Deceleration Phase
{Point to / Grasp} disk 	Point	2cm	20cm	34% ± 10.2
			40	34% ± 12.7
		4	20	33% ± 5.1
			40	30% ± 11.2
2 Widths 2 Amplitudes	Grasp	2	20	58% ± 2.3
			40	50% ± 4.6
		4	20	52% ± 1.8
			40	51% ± 2.6
Grasp {tennis ball / light bulb} 	Grasp ball	6	30	48% ± 3.8
Width fixed Amplitude fixed 2 Object properties	Grasp light bulb	6	30	51% ± 4.5
Grasp, then {throw / fit} 	Grasp and throw	4	30	46% ± 4.4
Width fixed Amplitude fixed Object properties fixed 2 Contexts	Grasp and fit	4	30	52% ± 5.4

could be a reliable measure for the precision needed in a task.

Less variability between conditions was seen in the early or acceleration phase of the movement, and more variability during the deceleration phase. Increasing precision requirements of a task may induce subjects to use more sensory information, particularly in the 'homing in' part of the task. Marteniuk et al. (1987) argued that the early part of the movement is more likely to be directly influenced by central stereotyped movement planning or programming, while the later part of the movement, during the deceleration phase, is using more sensorimotor adjustments for controlling the movement, causing more variability. Similar results were found by Paulignan, MacKenzie, Marteniuk, and Jeannerod (1991), who also showed that the variability in movements is not evenly distributed through the trajectory, noting more variability before peak velocity of the wrist is reached and less afterwards. This relates to what Jeannerod noted above, how an initial ballistic phase gets the hand into the vicinity of the target, and a second phase using feedback guides the hand to the target. It is worth noting that reaching to grasp differs from the pointing tasks discussed earlier, in which contact is not being made with a surface and results show symmetrical velocity profiles (Atkeson & Hollerbach, 1985).

Other researchers have contrasted reaching to grasp with reaching to point in order to examine the motor control of the arm. Using an ELITE system, Corradini, Gentilucci, Leo and Rizzolatti (1992) found only an effect of target size, not the distal task on the deceleration phase of the arm movement. They provided a computational model of the controller, ARMAX, with a model order which confirmed invariance of the control program with regard to movement amplitude, with sensitivity to the size (diameter) of the object. In contrast, Carnahan and colleagues (1992; Carnahan, Goodale & Marteniuk, 1993) present evidence that pointing and grasping are fundamentally different. Comparing moving and stationary targets, Figure 5.15 shows a disordinal interaction in which pointing is better for stationary targets and grasping is faster for moving targets. That the grasping system was better able to deal with target motion than the pointing system was also demonstrated in experiments in which the object location was perturbed. Carnahan discusses the adaptive functions of the design of visuomotor systems for pointing in a stationary environment (e.g., communication) and grasping to acquire objects in a dynamic environment (e.g., food, prey, defence, locomotion, etc).

Object velocity was more extensively investigated by Chieffi, Fogassi, Gallese and Gentilucci (1992) who showed that the speed of the arm movement covaried with the speed of the approaching object. Interestingly, they found that kinematic landmarks for grasping were unaffected by object velocity, as was the acceleration phase of movement, but transport parameters like peak velocity, and duration of deceleration phase were affected. Also, the spatial endpoints and paths were different in that as velocity increased, subjects grasped objects closer to the body. They suggested that object motion prior to grasping was an extrinsic object property in this grasping task and thus only affected the transport component.

The above evidence suggests that the task requirements for the

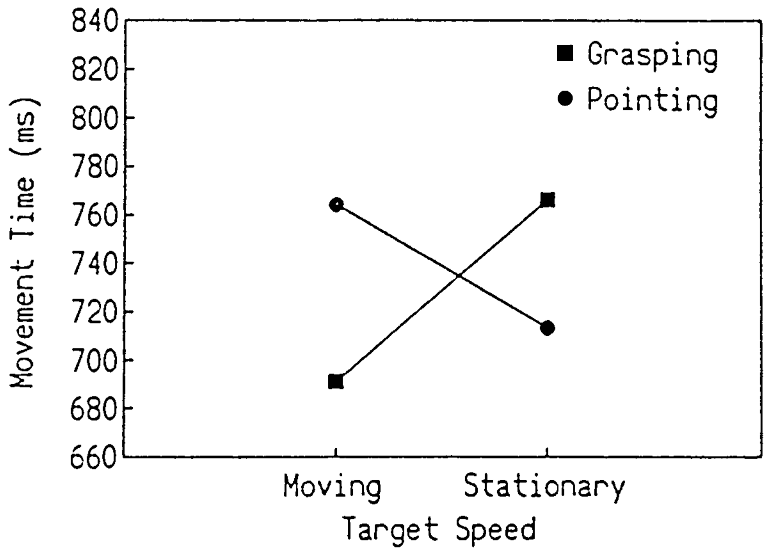


Figure 5.15 Movement time to point to, or grasp objects that were either stationary or moving (rolling down a ramp). Note that grasping movements were better adapted to moving targets, and that pointing movements were faster to stationary targets (from Carnahan, 1992; reprinted by permission)

hand, and the appropriate opposition space for making contacts with the environment are key variables in determining kinematic landmarks in the arm transport. Reaching with the arm to grasp with the hand is different from reaching with the arm to point. For grasping, an important question is whether and how the hand movements are coupled to the arm movements. Although we will address this in more detail later, Jeannerod suggested that they are under the control of parallel controllers that get coupled in time. Wing and associates (Wing & Fraser, 1983; Wing, Turton, & Fraser, 1986) argued instead for a spatial relationship between the arm transport component and the grasping component. In their experiments, subjects reached in the sagittal plane to grasp a vertically standing dowel under conditions where visual feedback and speed of movement varied. In all conditions, the thumb tended to move less than the index finger, especially after the fingers reached the peak aperture, as seen on the right side of Figure 5.16. In addition, in trials without visual feedback and also in the faster moves, subjects tended to open the hand wider, reaching a larger, and more variable, peak aperture. Wing et al. (1986) sug-

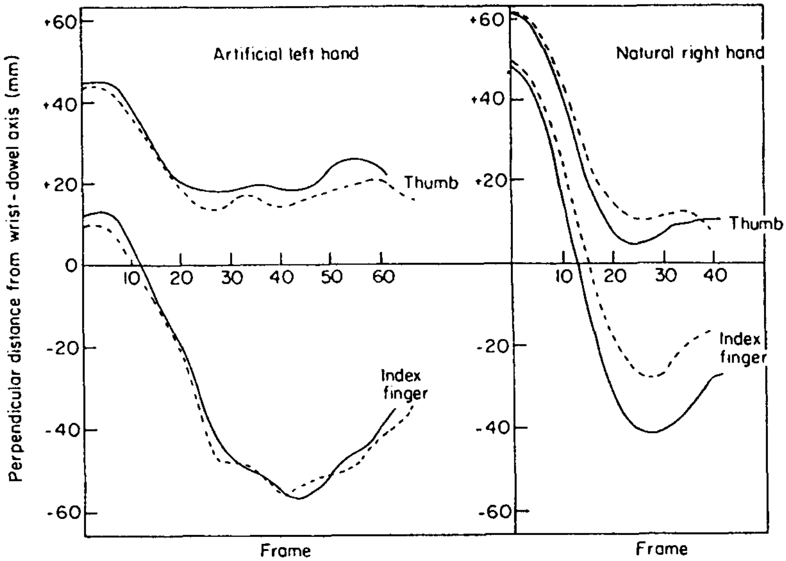


Figure 5.16 Thumb and index finger separating in order to grasp dowel. Note how index finger opens more than the thumb. The left side shows data from a 13 year old girl having a one degree of freedom prosthetic hand directing her thumb towards the cylinder. The same control algorithm is used by her normal hand, which is shown on the right side (from Wing & Fraser, 1983; reprinted by permission).

gested that with speeded movement, errors in transport could be compensated for by a larger aperture, showing the spatial coupling.

It is interesting to note what happens in conditions where a prosthetic hand replaces the human hand. Wing and Fraser (1983) studied a 13 year old girl who still moved the thumb less, even though the prosthesis had 1 degree of freedom. This forced her to rotate her forearm in order to maintain the same relationship between her prosthetic 'thumb' and the object (left side of Figure 5.16). Sometimes it was even necessary to reverse the direction of the hand transport in order to complement the effects of the wrist rotation.

Thus the speed demands of the task seem a key variable. Wallace and Weeks (1988) factorially combined distance and movement duration, suggesting that the maximum aperture was dependent on movement time, rather than movement speed per se. Like Marteniuk, MacKenzie, and Leavitt (1990), they suggested their pattern of results showed a strong functional linkage between the grasp and reach components.

Examining the variability of grasp movements as a function of movement speed and practice, the most striking finding was the invariance of the location of fingertip contact on the thumb (Darling, Cole & Abbs, 1988). Also, the movements of the thumb and index were not coplanar; the index finger was elevated .2 - .8 radians relative to the plane of the thumb tip movement. In contrast to arm movements, variability of end position of finger and thumb joint end positions did not increase with increases in movement speed. This was apparently due to an offsetting of the positional increases in variability during acceleration by the decreases in positional variability during deceleration. Rapid movements (100 ms duration) had bell-shaped single peaked velocity profiles, and the slower movements (200, 400 ms durations) had multiple peaks in the associated velocity profiles of joint angles of the thumb and index finger.

Wing and Fraser (1983) noted also the constant location of contact on the finger pads and suggested that the visual monitoring of the thumb allows it to be directed toward the object. This is a driving constraint in these types of movements, and therefore arm and hand control are not separable processes. Referring to the opposition space view presented in Chapter 4, with respect to directing the approach vector towards the opposition vector, these data might suggest that the the approach vector is directed to the opposition vector in the object at the location where the thumb makes contact. However, using graphics animation of WATSMART data for grasping, visualization of the approaching hand from the perspective of the object suggested that instead of being aligned along VF1 (the thumb), the approach vector from the hand to the object was aligned between VF1 and VF2 (Forsey & MacKenzie, unpublished).

Accessibility constraints can also affect the transporting of the hand to the object. MacKenzie, Sivak, and Iberall (1989) performed a screwdriver experiment, where subjects were instructed to reach and grasp a screwdriver, make 3-4 turns on a screw, and then replace the screwdriver. Four different sized screwdrivers were used, and the task (tighten a screw into a board) varied as well, depending on the size of the screws and whether or not the screwdriver handle was accessible. During the reaching to grasp the screwdriver, the peak speed of the wrist increased with screwdriver size. The accessibility of the screwdriver handle affected both the grasp and transport components: when the handle was accessible, grasping movements were slower, resultant velocity profiles were more asymmetrical, and a greater percent of time was spent after peak deceleration than when the handle was supported on the table. There was greater reposturing of the hand after first contact when the handle was on the table; in contrast, the longer deceleration phase when the handle was accessible may have reflected more precise hand placement at contact. This interacted with screwdriver size, such that the precision effects of handle accessibility were most pronounced for the smallest screwdriver.

With respect to intrinsic object properties, one of the most reliable and robust findings concerns the tightly calibrated relationship between object size (cylinder diameter) and maximum aperture. In Chapter 4, we noted that even when subjects do not grasp an object, they are able to match well with an unseen hand the required opening to grasp seen objects of various sizes (Jeannerod & Decety, 1990). Many investigators have studied the relationship between aperture evolution and object size (e.g., Gentilucci et al., 1991; von Hofsten & Ronnqvist, 1988; Jakobson & Goodale, 1991; Jeannerod, 1981, 1984; Marteniuk et al., 1990; Wallace & Weeks, 1988; Wing & Fraser, 1983; Wing, Turton & Fraser, 1986). Using 10 wooden disks (2.54 cm high, and 1 - 10 cm in diameter), placed 30 cm forward in the sagittal, midline plane, Marteniuk et al. (1990) had subjects reach to grasp, lift and replace the disks on the table top. They found that peak aperture increased by 0.77 cm for every 1 cm increase in the diameter of the cylinders, with a correlation of .99. The correlations between cyclinder diameter and peak aperture for individual subjects ranged from .992 to .998! Consistent with the findings of von Hofsten and Ronnqvist (1988) and Gentilucci et al. (1991), Marteniuk et al. (1990) found that maximum aperture was reached earlier (i.e., a greater time spent enclosing) when grasping a small object, compared to a larger one[15].

What about the relative time spent in preshaping and enclosing? Jeannerod (1981, 1984) suggested that the time to maximum aperture was about 75% of total movement time, compared to Wallace and Weeks, who reported 60% of MT in preshaping. Others (e.g., Gentilucci et al., 1991; von Hofsten & Ronnqvist, 1988) have reported that the relative timing of hand closure was related to object size. While it has been demonstrated that preshaping relates to visually determined object size (Marteniuk et al, 1990), shape (Jeannerod,

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[15] It is perhaps significant that infants 9-13 months old adjust their hands to target size, but not the 5 - 6 month olds (von Hofsten and Ronnqvist, 1988). It is usually between these times that pad opposition or precision grip appears.

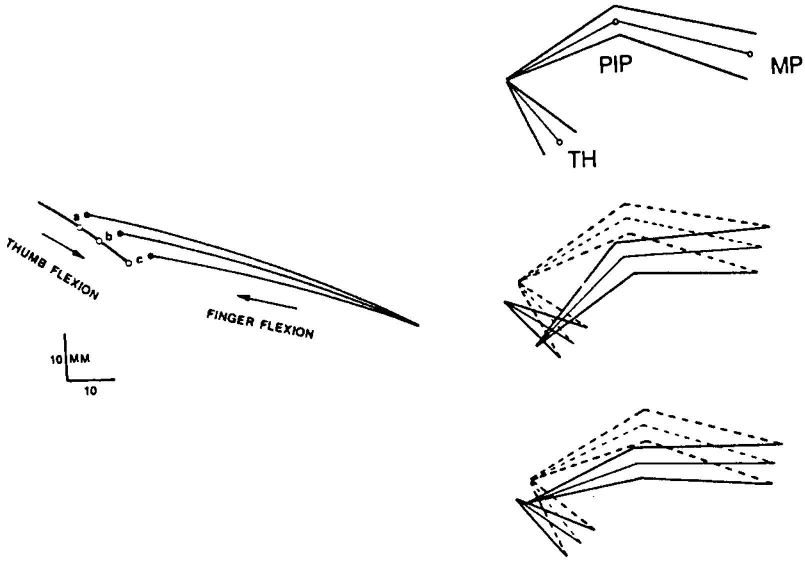

Figure 5.17. Finger and thumb joint adjustments during rapid pinch movements. On the left, the positions of the tip of the finger and thumb at contact (circles) for 3 trials (a,b,c) illustrating the covariable relation of the finger and thumb paths. On the right, a schematic shows configurations of the thumb interphalangeal joint (TH) and the finger proximal interphalangeal (PIP) and metacarpophalangeal (MP) joints. Top right figure shows a typical configuration at contact. Middle figure shows hypothetical configuration (solid lines) where pads miss making contact when only TH and MP flex. Bottom figure shows observed results of pads making contact because PIP and MP reciprocally adjust to TH flexion (from Cole & Abbs, 1986; reprinted by permission).

1981), and task (Arbib et al., 1985), what the goal of the enclose motion is is still unclear. Insights into this question can be gained by studying recent work in the area of rapid pinching tasks. Cole and Abbs (1986) asked subjects to perform rapid pinch movements in order to produce a specified finger-thumb contact force, as seen in Figure 5.17. Only movement at the interphalangeal (IP) joint of the thumb (TH) and at the proximal interphalangeal (PIP) and metacarpophalangeal (MP) joints were allowed due to constraints placed on the hand. Subjects repeated the task and maintained the contact force within the prescribed range, and while doing so, consistently brought the distal pulps into contact even though a great deal of variability was seen in the kinematic features. On the left of Figure 5.17, the positions of the finger and thumb tips are identified. The figure shows the covariable relation between thumb and finger paths. The goal of the task, to produce a required force, was consistently achieved although there were a wide variety of joint configurations and spatial paths in the thumb and index finger. On the right of the figure, Cole and Abbs showed hypothetical and observed configurations. The top figure shows an observed configuration. In the middle figure, hypothetical joint positions are shown, demonstrating that the distal pads will not make contact when the thumb IP joint extends but only the finger MP joint flexes. In the lower figure, Cole and Abbs showed actual observed actions; the pads are brought into contact from reciprocal adjustments of the PIP and MP joint in response to the thumb joint flexion.

The precision effect found by Marteniuk et al. (1987) is relevant to the difference between preshaping and enclosing. They argued that the early part of the movement is more likely to be directly influenced by central stereotyped movement planning, while the later part of the movement, during the deceleration phase, is controlled by feedback. Increasing the precision requirements of a task may induce subjects to use more sensory information, particularly in the 'homing in' part of the task, where the enclosing of the hand is occurring.

Jeannerod (1981, 1984) reported that object size affected only the grasp component, not the transport component. This finding was replicated by Wallace and Weeks (1988) in their examination of temporal constraints when grasping .3 cm or 2.5 cm dowels. In contrast, and for reasons which are still not clear, Marteniuk et al. (1990) reported an invariant time to peak deceleration, but a lengthening of the time after peak deceleration to object contact for the smallest object, consistent with the effects of target size on pointing. Contrary to independent channels for intrinsic and extrinsic properties, Jakobson & Goodale (1991) reported also that object size and object distance affected kinematic landmarks for both the transport and grasping components.

To now, we have considered only those intrinsic properties which can be assessed by vision, and were identified in Chapter 4. In all of the above studies of object size, object weight covaried with object size (Jeannerod, 1984; von Hofsten & Ronnqvist, 1988; Marteniuk et al, 1990), that is, the larger objects were always heavier. A set of experiments was designed (Weir, MacKenzie, Marteniuk, Cargoe & Frazer, 1991) to examine the effects of object weight uncontaminated by covariations in size, by using visibly similar cylindrical dowels of constant size (10.3 cm high and 2.5 cm in diameter), but varying in weight (from 20 to 410 grams). From a fixed starting position, and relaxed hand posture, with the thumb and index finger in contact over the table top, the task was to grasp and lift a dowel placed 30 cm in front of the body midline. Subjects grasped the dowels under blocked (weight known, since a group of trials had all the same dowel weight) and random conditions (weight unknown, with random variation of the different weighted dowels over trials). Markers were placed on the wrist, index finger and thumb. Using the WATSMART system (sampling at 200 Hz, reconstruction error of about 2.1 mm, filtering at 4 Hz using a second order Butterworth filter with dual pass), kinematics were analyzed from the time of hand lift to dowel lift.

Results revealed that, as expected, maximum aperture did not vary across the conditions, since the dowels were all of the same diameter. However, subjects spent a longer time after peak aperture and peak deceleration for the 410 gram dowel than the lighter dowels. Further, more time was spent in the deceleration portion of the movement on trials when the weight was unknown than when the weight was known. Visual examination of the wrist velocity and the aperture profiles suggested this longer time reflected 'tails' or unchanging velocity/aperture values at the end of movement, during the time when the subject was in contact with the dowel prior to lift (see Weir et al., 1991 for details). In a second experiment therefore, the time in contact with the dowel prior to lift was measured directly. A metal contact breaking system defined the times of hand lift, contact of the thumb and index finger with the dowel, and dowel lift. The results confirmed that the timing and kinematics of the movement prior to contacting the dowel were unaffected by the dowel weight or weight uncertainty. We were surprised to discover that, even for blocked trials when subjects knew the weight of the dowel, there were no anticipatory changes in the kinematics prior to contacting the dowel. Since the dowels were visibly similar, this emphasizes the dominance of visual information prior to contacting the object, and the influence of tactile and kinesthetic information once contact is made. All the timing and kinematic effects occurred after contacting the dowel, prior to lift off. The time spent in contact with the dowel prior to lift increased systematically with dowel weight. More time is spent in contact with the dowel prior to lift when the weight is unknown than when the weight is predictable based on previous trials. This increased time spent in contact with the dowel is consistent with research showing that the functions for grip and load force application over time had an increased slope and longer duration prior to lift for heavier objects (Johansson & Westling, 1988b), to be discussed in Chapter 6.

A similar experiment was conducted to examine the effects of object texture, which can be partially assessed by vision (Weir, MacKenzie, Marteniuk, Cargoe & Fraser, 1991). Subjects reached, grasped and lifted slippery (coated with vaseline), neutral (polished metal) or coarse (covered in sandpaper) dowels in blocked conditions. Results indicated that a longer time was spent in contact with the slippery dowel, prior to lift, compared with the other two dowels. They suggested that even though the texture information was available during vision, the kinematics prior to contact revealed no anticipation appropriate for the coefficient of friction at contact. Replicating and extending this study, Fikes, Klatzky and Lederman (1993) showed that under randomized conditions, reaching for a slippery dowel, individuals spent a greater time from movement onset to contact. They discussed these results in terms of the greater geometric and dynamic precision required for lifting a slippery object. Given the lower coefficient of friction, subjects might adapt to the frictional requirements in two ways: post contact (as demonstrated by Johansson and Westling, 1984b) or precontact. Fikes et al. suggest that they may prepare appropriate grip geometry precontact, and the associated precision for placement anticipating slip might take more time. This is an important suggestion, because such placement precision demands should be quantifiable in kinematic landmarks prior to contact.

In this section, we have seen how intrinsic object properties like size and weight, and extrinsic properties like distance, direction, object motion and surface texture affect kinematic landmarks of the reaching and grasping components. In examining task requirements, the evidence seems to indicate that reaching with the arm to point is very different from reaching to grasp, and further that the requirements for the hand are 'driving the arm'. The kinematics of reaching and grasping reflect the setting up of opposition space parameters, and the anticipatory preparation for task demands once the object is grasped. The arm and the hand seem to be functionally coupled in their control.

5.4.2 Visual and mechanical perturbations to grasping

Additional evidence for the view that the arm and hand are functionally coupled to align the grasping surface patches on the hand with the opposition vector is derived from perturbation studies. We consider mechanical perturbation studies, where unexpected loads are applied to oppose or interfere with the ongoing movement (as in being bumped while reaching to grasp an object). As well we consider visual perturbation studies, which change the object characteristics in some way (as when an object moves unexpectedly). These two approaches to perturbation share the view of probing the controller, examining how information is used in sensorimotor integration to achieve the grasping goals in setting up opposition space. With mechanical perturbation studies, in addition to sensory information from proprioceptors (cutaneous, joint, muscle and tendon receptors in the entire limb), there are corresponding, complex alterations in limb dynamics which the controller takes into account. With visual perturbations, mechanical responses in the limb to perturbation are not evident; the visuomotor integration processes can be inferred from changes in the kinematics of grasping.

Examining multiarticulate hand movements, in analogy to unexpected perturbations in speech and postural control, Cole, Gracco and Abbs (1984) trained human subjects to generate rapid movements of the thumb and index finger in pad opposition to produce a controlled pinch contact force of 1 N. The hand was splinted to restrict available motion to the interphalangeal joint of the thumb and the metacarpophalangeal joint of the index finger, so that the pads could be brought into opposition. On 13% of trials, <u>a force opposing thumb flexion</u> was delivered (1.9 N, rise time 15 ms, sustained throughout the movement), within an interval 70 ms prior to activation of the flexor digitorum superficialis (the index finger flexor here). On perturbation trials, the desired contact force was achieved by rapid compensatory adjustments in both the thumb and the index finger. They reported that these adjustments: had latencies of 60 - 90 ms; were manifest even with the first perturbation and; were absent for loads opposing thumb movement during a nonprehensile task. Cole et al. suggested that this context dependency of the finger flexion responses extends the work of Traub, Rothwell and Marsden (1980) who reported a 'grab reflex' or 'sherry glass response' whereby, regardless of loading or unloading of the thumb flexor muscle (flexor pollicis longus) by mechanical perturbations to the wrist, the functional response was to maintain grasp, dependent and adapted to the task and the intent of the individual to maintain the digits in contact with the object.

In a followup study, Cole and Abbs (1987) showed that the system's response to an unexpected perturbation is to maintain the high level goal of bringing the finger pads into contact to maintain the required force generation. If the thumb was perturbed, there was a short latency response (about 60-90 ms) and the system, through a very different kinematic pattern, still achieved the goal of the criterion force between the thumb and index. Of interest in these studies was the observed invariance of the contact point between the thumb and index finger. In all conditions, the subjects maintained the contact on the finger pads, the location of specialized cutaneous mechanoreceptors. Cole and Abbs further argued that the goal of contact was in sensory terms; i.e., maintaining the same cutaneous input and achieving the required force. In terms of enclosing the hand during prehension, perhaps the goal is to bring the chosen pads (for pad opposition) into a specific contact with the object. It is obvious from these data that the CNS knows the direction that the pads are pointing.

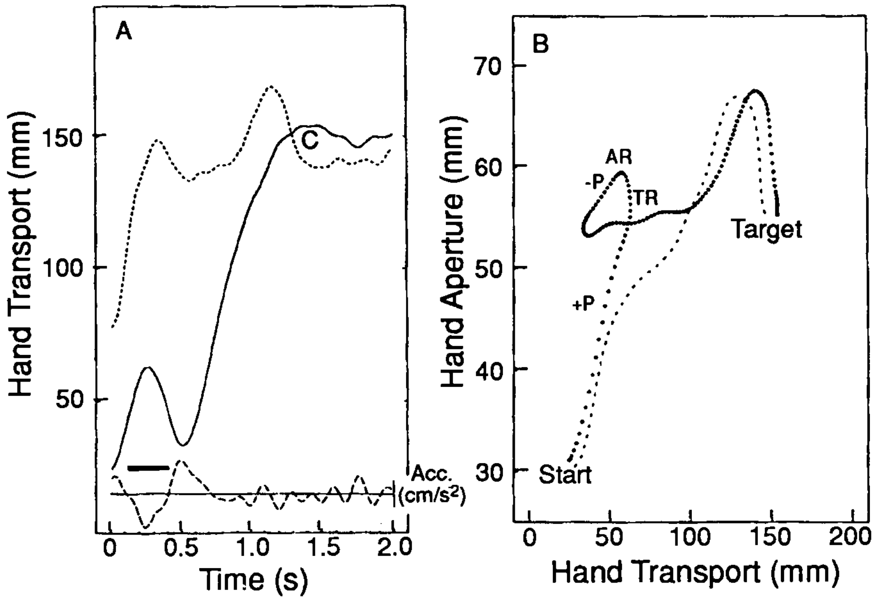

Figure 5.18 A single trial in which a mechanical perturbation pulled the arm backwards, and both transport and aperture reversals were observed. A. Shows hand transport (solid line, left axis) and grip aperture (dashed line, right axis). The acceleration is double differentiated from the hand transport (long dashed lines, axis ± 1 cm/s/s). The solid horizontal bar represents a pull perturbation of 15 N. B. For the same trial as A, a spatial plot of hand aperture against hand transport. The perturbing force began at +P, the transport reversal began at TR, the hand aperture reversal at AR and the perturbing force offset at -P. Perturbed trial shows a distinct loop at reversals; the control trial is a dashed line (from Haggard & Wing, 1991; reprinted by permission).

In contrast to the above studies, Haggard and Wing (1991) introduced mechanical perturbations of the arm, and looked for compensatory responses in hand aperture. They used a torque motor to deliver pulling or pushing forces on the arm (extending the shoulder, and moving it backwards from the target, or flexing the shoulder and moving it towards the target). Perturbations occurred on 25% of the trials (randomly between 1 and 560 ms after trial onset; net force 5,10, 15, or 20 N, for 250 ms duration). Push perturbations did not disrupt hand transport and were unnoticed by the subjects. In contrast, pulling the arm backward from the target showed disruptions through 'transport reversals', i.e. changes in direction of hand transport (typically, about 120 ms after perturbation). Figure 5.18 shows the pattern obtained on 67% of perturbed trials with transport reversals where 'hand-aperture reversals' were observed also (about 70 ms later than the hand transport reversals, or 100 ms after the backwards acceleration). On these trials, hand aperture would continue to increase for a short time after hand transport had been slowed. As the hand began to be pulled backwards, hand aperture would decrease for a short time. Then, after the perturbation ended, the hand's transport towards the target would resume, followed by resumption of grasp opening. Haggard and Wing suggested the hand aperture reversals were not a biomechanical result of the perturbation because of the long latencies; rather they suggest that information about the two effector systems is monitored for sensor-based coordination and control. The latency of over 100 ms from arm transport reversal to aperture reversal appeared to them more consistent with a voluntary response than a spinal reflex. They suggested that the compensatory response returns the subject to the spatial track they had before the perturbation, and that the spatial basis for coordination of transport and grasp is an important one.

Visual perturbation experiments have shown also a functional coupling between transport and grasp components. Like Haggard and Wing, the perturbations have affected both transport and grasp components but with different times required to reorganize each component. A repeated finding is the linking of deceleration of hand transport with aperture closing, and reacceleration of the limb with hand opening, or aperture increase. These perturbation studies have, through optical and illumination techniques altered the distance, direction, shape and size of the object to be grasped. First we consider the extrinsic object properties of direction and distance, then we consider object shape and size perturbations.

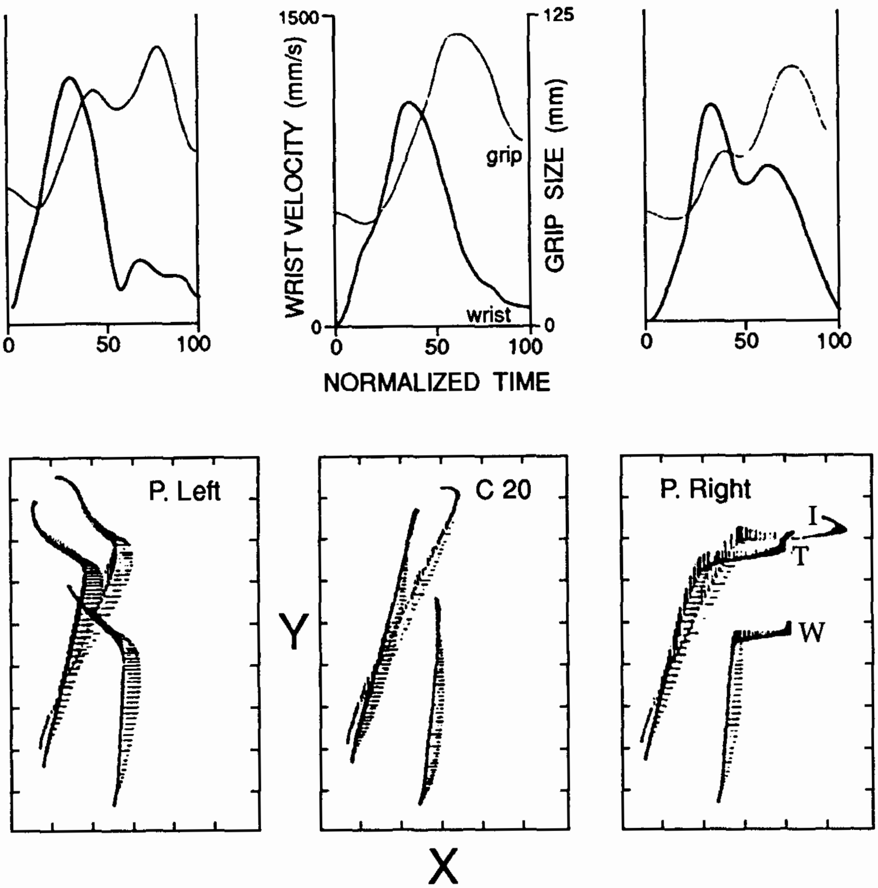

Figure 5.19 Perturbations of object direction. Top row: Kinematics of transport of the wrist (dark line) and grip aperture (light line) for perturbed-left, control, and perturbed right conditions. Note the compensations to perturbation in both the grasp and transport kinematics. Bottom row: Spatial paths and their variability for the wrist (W), index finger (I) and thumb (T). Note the greater contribution of the index finger than the thumb to enclosing, but that this varies with condition (reprinted by permission from Jeannerod & Marteniuk, 1992).

To perturb object direction, Paulignan, MacKenzie, Marteniuk, and Jeannerod (1990, 1991) had 3 translucent dowels, placed 30 cm away on a table, at 10, 20 and 30 degrees from the body midline. In blocked and control (nonperturbed) trials, one dowel was illuminated and served as the target object. On 20% of trials, the first, center dowel was illuminated, and at movement onset, the illumination unexpectedly shifted left or right to another dowel. Subjects were instructed to grasp the illuminated dowel with pad opposition. Relative to control trials, movement time on perturbed trials increased by 80 and 112 ms for perturbed-left and perturbed-right trials. Shown in Figure 5.19, on perturbed trials, the transport of the hand showed an abrupt change in direction at about 255 and 295 ms, corresponding to the new target object (left and right respectively). Evidence for the first change in the transport kinematics was that peak acceleration occurred earlier in the perturbed conditions (about 100 ms) compared to the control conditions (130 ms). Interestingly, on perturbed trials the time between the two peaks in velocity was about the same as the time from movement onset to the initial peak velocity, about 180 ms. Although the perturbation affected no intrinsic object characteristics, there were corresponding changes in the grip aperture, such that there were two peaks in the aperture profile on most trials. At around the time that the transport component was reoriented, the preshaping phase was interrupted, and the hand began to close. The first peak in grip aperture was smaller and earlier than in control trials, and the second peak corresponded to the magnitude of peak aperture for control trials. Paulignan et al. showed that the variability of spatial paths was at a maximum around the time of peak velocity and decreased steadily as the finger pads converged onto the object locations. They argue that this might reflect two separate phases, where the first phase is involved in directional coding of the movement; in contrast, the second phase would involve comparisons between motor commands and sensory feedback. The acceleration phase was interpreted as reflecting mechanisms for directional control of movement. In contrast, the deceleration phase reflects sensorimotor-based control based on interaction between motor output and reafferent signals, visual and proprioceptive. The reader is referred to related studies on pointing by Pelisson and colleagues (Pelisson, Prablanc, Goodale & Jeannerod, 1986; Prablanc, Pelisson & Goodale, 1986).

To perturb object distance, Gentilucci, Chieffi, Scarpa and Castiello (1992) had subjects grasp 3 spheres (diameter 4 cm) placed at 15, 27.5 and 40 cm from the starting position along the subject's sagittal plane. Subjects grasped the illuminated sphere using pad opposition. On 20% perturbed trials, the nearest sphere was first illuminated, then at movement onset one of the more distant spheres became illuminated. They found two clear submovements on perturbed trials, with the second movement aiming to the more distant target occurring at about 370 ms. Following Paulignan, MacKenzie, Marteniuk, and Jeannerod (1990, 1991), evidence for the first change in the transport kinematics was that peak acceleration occurred earlier in the perturbed conditions (about 150 ms) compared to the control conditions (186 ms). The values of peak acceleration did not differ between the two perturbed conditions, thus they concluded that the first movement was interrupted by the visual perturbation. The beginning of the second grip occurred significantly later for trials perturbed to 40 cm than for trials perturbed to 27.5 cm. Like Paulignan et al., the manipulation of an extrinsic object property (in this case distance) affected both transport and grasping components. They acknowledge that the two targets presented in succession may require two separate motor plans, hence two submovements and two grip apertures. They note the importance of their finding that finger closure time remained invariant over distance and experimental perturbation conditions.

Perturbing object orientation and position, Stelmach, Castiello, and Jeannerod (1993) found that if the perturbation required addition of a pronation component to orient the hand, there was a corresponding increase in movement time, and the time devoted to deceleration of the hand was lengthened. These findings were interpreted as indicating the necessity for a kinematic rearrangement with the addition of a pronation component due to perturbation; in contrast, the pronation component can emerge as part of the motor plan in natural, unperturbed prehension.

Introducing the visual perturbation paradigm to study intrinsic properties in motor interactions with objects, Jeannerod (1981, Experiment 2) used an ellipsoid object (axes: 7 cm and 4 cm) placed above a mirror. To perturb object shape, rotation with a small motor made the object appear spherical (4 cm). Each trial started with presentation of a sphere. At the onset of movement, on perturbed trials, with rotation of the object, the mirrored reflection of the sphere appeared to expand suddenly to an elliptical object. For perturbed and unperturbed trials, the physical object of the corresponding target shape was placed at the expected location on the table, so that the shape of the object actually grasped always corresponded to the virtual image present in the mirror at the same time. Jeannerod reported that the shape and shape change of the target object had no effect on the transport component. In contrast, there were obvious differences in anticipatory hand posturing between the egg-like object and the spherical one. On perturbed trials, when the sphere suddenly expanded to appear egg-like, the first evidence for alterations in hand configuration occured at least 500 ms after perturbation onset. He noted this time required elaboration of new commands, and the configuration of a new, appropriate grip pattern before the beginning of finger closure.

Thus, in contrast to the short times for compensation to visual perturbation of extrinsic characteristics, it appears that perturbing intrinsic object characteristics requires a longer time to reconfigure the opposition space parameters. In a larger experiment (more subjects, more trials with a computerized motion analysis system), with perturbations to object size both grasp and transport components were affected (Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991). Using pad opposition, subjects grasped one of two, nested dowels, placed 35 cm away. The inner, 'small' dowel was 10 cm high and 1.5 cm in diameter; the outer, 'large' dowel was 6 cm high and 6 cm in diameter. On 20% perturbed trials one of the two translucent dowels would be illuminated, then at movement onset, the illumination would suddenly switch to the larger (S->L) or smaller (L->S) dowel, giving the impression of an expanding or shrinking dowel respectively. Results showed that movement time for S->L trials, requiring a change in direction of planned aperture size (i.e., a reopening, compared to initial selection), increased by 175 ms, whereas L->S trials, requiring a change in magnitude of planned aperture size (i.e., greater closing), increased by only 98 ms. Compared to control, unperturbed trials, none of the kinematic landmarks up to peak deceleration were affected by the perturbation; all changes to the transport kinematics occurred after peak deceleration (about 300 ms), during the low velocity phase. Shown in Figure 5.20, grip formation for the S->L perturbation showed a first peak (corresponding in time and amplitude to the peak aperture for the small dowel in control conditions), some discontinuity, then reincreased to accommodate the size of the new dowel. This reincreasing occurred 330 ms after movement onset (as determined from the grip velocity profile), after peak deceleration. The time between the two peaks in grip aperture for S->L was about 180 ms. The aperture evolution for the L->S perturbation was much attenuated, showing no discontinuities and only one peak, and identical to control large conditions, except for a longer enclose phase, until the fingers reached their contacting locations on the smaller dowel. Remarkable in these data was the low variability in the spatial paths of the hand, as enclosing occurred. This

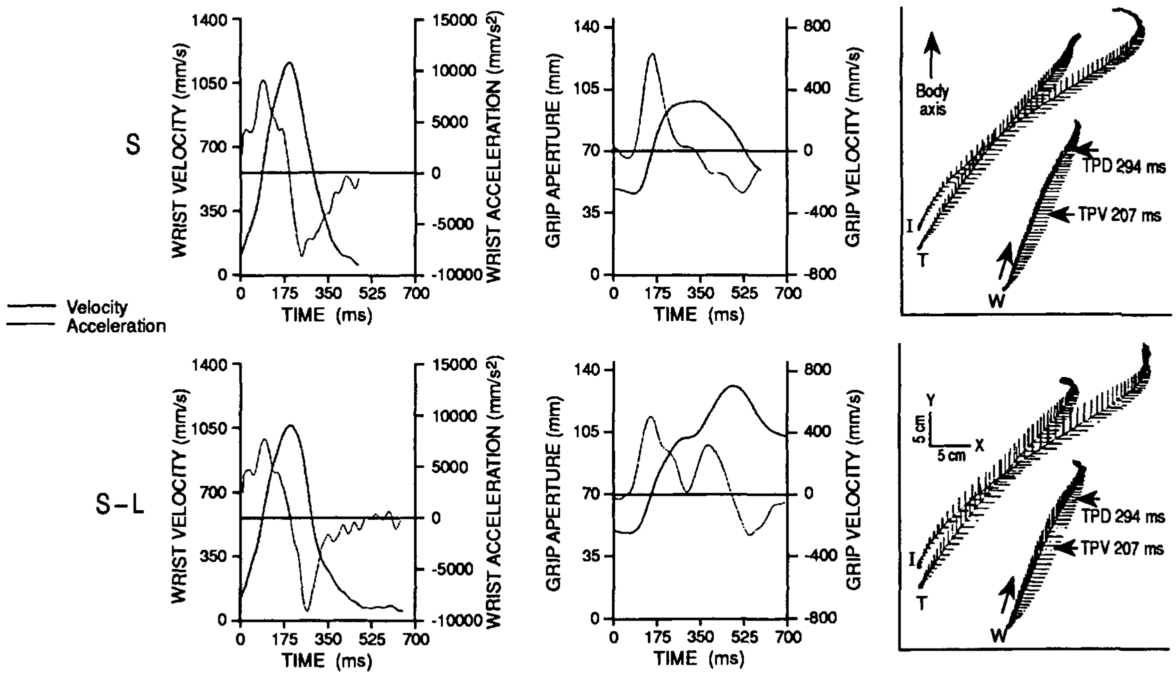

Figure 5.20 Kinematics of hand transport, grip formation and spatial path in the small control and small-to-large perturbed (S->L) conditions. Top row: small dowel control, unperturbed trials, Bottom row: small-to-large perturbed (S->L) trials. Left to right: hand transport, grip formation and spatial path (from Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991; reprinted by permission).

spatial variability was no greater on perturbed trials than on control trials, reminiscent of Haggard and Wing's (1991) suggestion that compensatory response return/place the hand to the spatial track required by that opposition space being set up.

Paulignan, Jeannerod, MacKenzie, & Marteniuk (1991) discussed that the longer time for corrections to perturbations of intrinsic object properties like object shape and size reflected the underlying central, cortical mechanisms for visuomotor processing of intrinsic object properties and controlling distal movements of the hands and fingers (see Jeannerod, 1986). In contrast, the more rapid adjustments to direction and distance reflect the pathways for visuomotor processing related to reaching, which may have a shorter time constant. In this regard the spinal reaching circuits discussed earlier have been implicated in visually guided target reaching in cats (Alstermark et al., 1990). Regardless, the requirements for the hand are still driving the arm, and the two must be coordinated in time and space to set up opposition space. We suggest as a working hypothesis that the goal driving the trajectories is the alignment of the grasping surface patches of the hand with the seen opposition vector, given the opposition space parameterization appropriate for the task.

In the direction perturbation studies of Paulignan, MacKenzie, Marteniuk, and Jeannerod (1991), recall that the illuminated dowel switched positions at movement onset. In these studies, there was an apparent <u>dissociation between the rapid motor corrections associated with this perturbation, and subjects' subjective awareness</u> of the occurrence of the target switching (Paulignan et al., 1990). That is, subjects reported perceiving that a dowel switched locations when the hand was almost at the first illuminated dowel, some time after the initial adjustments (at about 100 ms) in limb transport had been made. To obtain objective measures of both the motor response to the perturbation, and subject's awareness, Castiello, Paulignan and Jeannerod (1991) replicated Paulignan et al. (1990) and asked subjects to signal the time at which they became aware of dowel displacement by a single utterance (Tah!). In contrast to the rapid limb response to perturbation (first acceleration at 107 ms), the vocal response indicating awareness of perturbation occurred 420 ms following object displacement, or more than 300 ms after the onset of the limb transport correction. They performed appropriate control experiments, showing that the dual task requirements did not interfere with one another, i.e., the dual task values were similar to those obtained from single task control experiments. Similarly, Castiello and Jeannerod (1991) compared manual adjustments to perturbations of object size with vocal responses indicating awareness of shifts in object size, and found latencies of about 424 ms, close to the vocal latencies of 420 ms reported by Castiello et al. (1991) for awareness of shifts in object direction. This similarity in times, combined with other research, led Castiello, Paulignan and Jeannerod (1991) to suggest the invariant time delay reflected a time consuming process for access to awareness of a visual event. They suggested that neural activity for processing information must be ongoing for a significant amount of time before it can give rise to conscious experience.

Almost all of the kinematic studies of prehension reviewed to this point have used naturally occurring or experimenter-defined pad opposition (precision grasp). We saw in Chapter 2 the extensive classifications of grasp types, and suggested these could be captured as pad, palm and side opposition. We consider briefly now studies which have examined different grasp types, then the underlying neural substrates for visuomotor integration with different oppositions.

5.4.3 Grasp types

The type of grasp posture used could potentially affect the kinematic components of reaching and grasping. We saw in Chapter 2 the variety of postures which could be adopted to match the task-specific object properties. In an important size perturbation study, Castiello, Bennett and Paulignan (1992) repeated the Paulignan, Jeannerod, MacKenzie, and Marteniuk (1991) size perturbation experiment, but encouraged subjects to adopt a natural grip appropriate to the diameter of the dowels. Thus subjects grasped 1.5 cm diameter objects with pad opposition using the index finger and the thumb (precision grip), or they used palm opposition (whole hand prehensile grip), with all fingers wrapped around the 6 cm dowels. The smaller dowel was nested inside, and protruded above the larger one. Visual perturbations of object size required a change in the distal program for hand configuration, and therefore a selection of a different opposition type. The responses to the perturbation showed that the first kinematic landmark for adjustments to perturbation was the time to peak deceleration (290 ms after perturbation of size), which occurred earlier on perturbed than on control trials. Further, time to peak deceleration was significantly earlier with perturbations from large to small objects (requiring palm to pad opposition) than vice versa. Contrast this first kinematic landmark of adjustment to perturbation with the apparent interruption in the acceleration, i.e., earlier time to and lower value of peak acceleration, for perturbations of direction reported by Paulignan et al. (1990). This is a large and important difference. Again for the small to large perturbations, there was a two peaked pattern in the grip aperture, but only a single peak in grip aperture for the large to small perturbations. The first kinematic landmark of corrective digit movement to switch from pad to palm opposition was at 342 ms, derived from the grip velocity profiles. Thus these changes in hand configuration took at least a visual reaction time, and were always preceded and facilitated by changes in the deceleration of the limb. They considered that the proximal control channel uses information about object size to modify the duration of its low velocity phase. Object size seems to determine the computational requirements of networks for both distal and proximal control.

The perturbation study of Castiello, Bennett and Paulignan (1992), using pad opposition for small and palm opposition for large cylindrical objects points to the importance of considering different opposition types, given object characteristics and task requirements. They showed that when human subjects grasped small dowels (1.5 cm diameter) using pad opposition, and larger dowels (6 cm diameter) using palm opposition in blocked sets of trials, the following differences were observed: movement times were longer for pad opposition (574 ms) than palm opposition (552 ms). This increased time was spent in the deceleration phase of the movement (374 ms for pad opposition vs. 353 ms for palm opposition). Castiello, Bennett & Paulignan's (1992) analysis of normalized data on unperturbed trials revealed that the two velocity functions did not belong to the same family of curves, i.e., a greater proportion of time was spent in the deceleration phase when using pad opposition compared to palm opposition. The aperture profile revealed, as expected, a larger maximum aperture between the thumb and index finger for the larger object using palm opposition (128 mm) than for the smaller object using pad opposition (92 mm). Peak aperture occurred during the deceleration phase, earlier for pad than palm opposition, and subject spent a greater proportion of time enclosing with pad opposition (42%) than with palm opposition (37%). Thus the increased precision requirements of grasping the small object in pad opposition appear to have influenced both transport and grasp components, leading to a longer time spent in the second 'homing in' phase of the movement. These results replicated closely an earlier study by Gentilucci, Castiello, Corradini, Scarpa, Umilta and Rizzolatti (1991) who found the effects of grasp type always additive to their distance manipulations.

Related findings were reported by Sivak (1989, Experiment 5) who had subjects reach for a dowel (2.5 cm diameter) placed 30 cm in

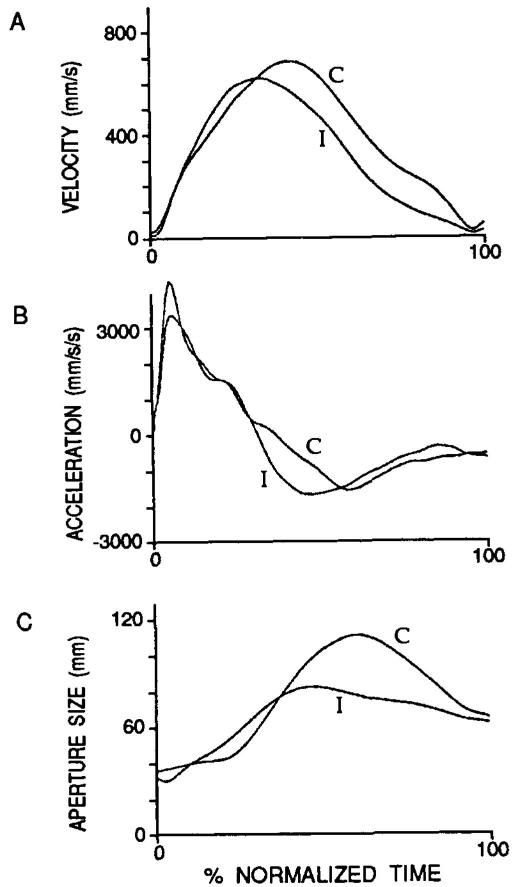

Figure 5.21 Grasping for a dowel 2.5 cm in diameter with pad opposition, using independent fingers (I) or palm opposition using collective fingers (C). A. Representative resultant velocity profile for wrist IRED marker from one subject B. Acceleration profile of wrist marker, derived from differentiating the tangential velocity profile. C. Aperture evolution for Collective and Independent finger grasps. Note the larger aperture for collective finger movements, even though both grasp types were used for the same sized dowel. Note the greater time spent in the deceleration phase with independent finger movements in pad opposition, compared to collective finger movements in palm opposition (from Sivak, 1989; reprinted by permisssion).

front of the start position, along a midline sagittal plane. Note an important difference from Castiello et al. (1992): in Sivak's experiment, the intrinsic and extrinsic object properties remained constant, ie., the retinal image about intrinsic and extrinsic dowel properties remained invariant. Only grasp type changed. In blocked trials, subjects used pad opposition, making contact with the thumb and index finger pads, or palm opposition, making first contact with the palm of the hand while the fingers and thumb enclose the dowel. Replicating Castiello et al.(1992) she showed that movement time and the proportion of time spent in the deceleration phase of movement was longer when reaching for dowels using pad opposition. For pad opposition, subjects spent 40% of MT or 385 ms after peak deceleration; in contrast, they spent 21% or 184 ms after peak deceleration when using palm opposition (see Figure 5.21). For the grasp component, even though the dowel size remained constant, the hand opened wider with palm opposition (107 mm), than with pad opposition (79 mm). Sivak noted that with pad opposition, for all subjects, peak aperture occurred after peak deceleration, but peak aperture between the thumb and index finger occurred before peak deceleration in palm opposition trials (for 5 out of 6 subjects). The relative time of maximum aperture did not change between the two grasp types (about 34% of time spent enclosing after peak aperture, with both grasp types), but the relative time spent in deceleration was longer for pad than palm opposition. These findings led Sivak (1989) to suggest that the neural processing in organizing the size of the aperture may be independent from the neural processing organizing the timing of maximum aperture. Sivak suggested that more time is needed in the final phase for precision tasks like pad opposition. With pad opposition, precise placement of the fingers was required; in contrast, with palm opposition, the object was acquired after initial contact with the palm. Related precision requirements were seen also in Marteniuk et al. (1987, 1990), with different tasks and different size disks.

What is the relationship of pad and palm opposition to dowel size? Castiello et al. (1992) stressed the importance of a natural mapping between object size and type of grasp. Small cylindrical objects are often grasped with pad opposition and as object size increases, aperture increases, more fingers are added to oppose the thumb, and eventually a palm opposition emerges. Sivak (1989, Experiment 6) investigated the sensitivity of palm and pad opposition to object size, reasoning that palm opposition (grasps using the fingers collectively) may not show the same robust effects of object size as pad opposition demonstrated previously by von Hofsten and Ronnqvist (1988) and

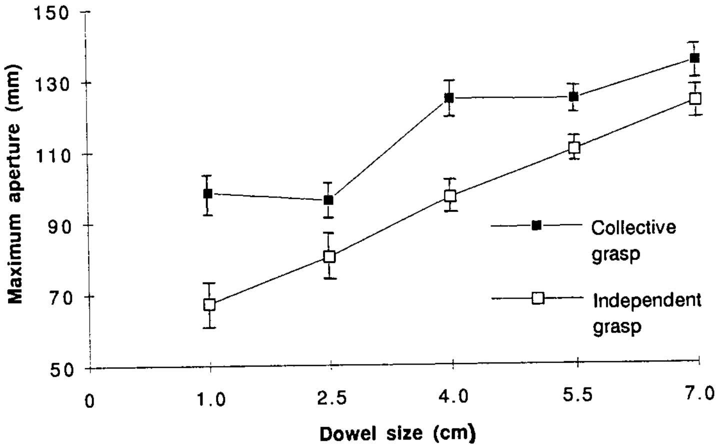

Figure 5.22 Peak aperture as a function of dowel size (1.0, 2.5, 4.0, 5.5 and 7.0 cm in diameter) when grasping with pad opposition, using independent fingers or with palm opposition, using collective fingers. In all cases, maximum aperture is greater when using the fingers collectively than when using the fingers independently, in pad opposition. Note the greater sensitivity to object size with independent finger movements in pad opposition, compared to collective finger movements in palm opposition (Adapted from Sivak, 1989; reprinted by permission).

Marteniuk et al.(1990). She used wooden dowels 1.0, 2.5, 4.0, 5.5 and 7.0 cm in diameter. Movement time and transport parameters did not show a clear monotonic change with dowel diameter. Rather, the 4 cm dowel seemed "easier" to grasp, had shorter movement times, higher peak velocities, and less time spent in deceleration. This result suggested that the 4.0 cm dowel could accommodate both independent and collective grasps quite easily. Shown in Figure 5.22, we see that earlier results were replicated, aperture was wider with palm opposition (collective grasp) than with pad opposition (independent finger grasp); further, with pad opposition there was a monotonic increase in maximum aperture with dowel size. In contrast, there appeared to be two groupings of maximum aperture with collective finger use in palm opposition: one, smaller, for the 1.0 and 2.5 cm dowels, and a second, much larger maximum aperture for the 4.0, 5.5 and 7.0 cm dowels. The second set may be reflecting a ceiling effect due to biomechanical constraints of the hand, ie., the hand was unable to open wider! Thus palm opposition, with contact on the palm, and finger enclosure to capture the object into the palm of the hand did not require precise finger placement; this type of grasp always had a wider aperture, and did not show precise calibration to object size in the same way as peak aperture with pad opposition.

The palm and pad oppositions described in the above studies differ in at least two distinct and important ways: the parts of the hand used in opposition (i.e., fingers opposed to the palm or thumb), and the number of fingers used in the opposition. With palm opposition, typically all (or most) of the fingers on the hand are flexed collectively to apply force in opposition to the palm. In contrast, with pad opposition (or precision grip), opposition is between the thumb, and the index finger. Thus, for pad opposition in the above experiments, VF1 is mapped onto the thumb, and VF2 is mapped onto the index finger; but VF2 could be mapped also onto any number of other fingers in opposition to the thumb. For example, VF2 could be index and middle fingers or VF2 could be index, middle, ring and little fingers used in opposition to VF1. Are the differences in these experiments due to the use of independent vs collective fingers, or due to pad opposition requiring precise placement of the fingertips vs palm opposition?

To answer this question, Sivak (1989, Experiment 7) suggested that if precision requirements of finger placement could be equated between collective and independent finger movements, one might predict no differences in the transport component, or in maximum aperture. Three grasp types were used: pad opposition with thumb and index (called independent grasp), palm opposition (called collective grasp, no precision),and pad opposition with the thumb opposed to pads of the four fingers (called collective grasp with precision) and three dowel sizes (2.5, 4.0, and 7.0 cm in diameter). As in all previous experiments, movements were 30 cm forward from the starting position of the hand, in the midline sagittal plane. The results of <u>kinematic analyses of the transport component showed that when pad opposition was required, it didn't matter whether there were one or four fingers in opposition to the thumb</u>. However, using the fingers collectively in palm opposition was different from the two pad opposition conditions. Using the fingers collectively in palm opposition had the highest kinematic peaks, a shorter deceleration phase, and a shorter per cent of time after peak deceleration. These robust, reliable effects were shown by all six subjects. A similar grouping of the grasp types was seen in the peak aperture data, shown in Figure 5.23. Note that using palm opposition (CNP, using collective fingers with no precision) had a larger maximum aperture in all cases. However, for the 2.5 cm dowel, the peak aperture for pad opposition with collective

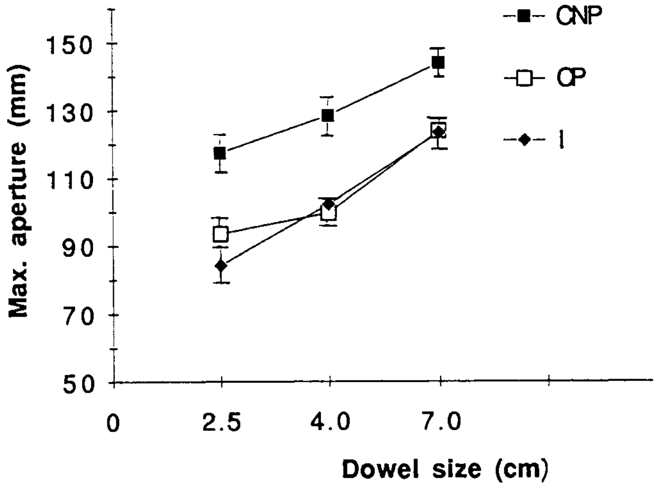

Figure 5.23 Peak aperture as a function of dowel size (2.5, 4.0, and 7.0 cm in diameter) when grasping with pad opposition, using independent fingers (I), with pad opposition using the four fingers collectively in opposition to the thumb (CP) or with palm opposition, using collective fingers and no precision (CNP). In all cases, maximum aperture is greater when using the fingers collectively in palm opposition than when using the fingers in pad opposition, either independently or collectively. Note the exceptional point is for the smallest dowel where the maximum aperture is slightly greater in pad opposition with collective fingers that in pad opposition between the thumb and index finger. Linear regressions of maximum aperture (cm) as a function of object size for each grasp type revealed: a) for I: Y = 6.48 + .85X b) for CP: Y= 7.44 + .69X c) for CNP: Y = 10.3 + .58X. These slope values, for dowels 11.5 cm high can be compared with Marteniuk et al. (1990) who found Y = 4.89 + .77X for disks 2.5 cm high (Adapted from Sivak, 1989; reprinted by permission).

fingers (CP) was slightly higher than for pad opposition with independent fingers (IP). This point led to a difference in the slopes computed for the three functions plotted in Figure 5.23. Note the slope of the function relating maximum aperture to cylinder diameter is the steepest for the describing pad opposition with VF2 as one finger, then pad opposition with VF2 as four fingers, and shallowest for the function describing palm opposition.

The above findings provide strong support for the distinction between pad and palm opposition as separate prehensile categories, for planning and/or execution. Once pad opposition is chosen, either one or more fingers can be mapped onto VF2, to oppose the thumb as VF1. In Sivak (1989) the transport velocity and deceleration phase of the movement was sensitive only to the distinction between pad and palm opposition. For cylindrical objects 2.5 cm in diameter or less, the number of real anatomical fingers mapped onto VF2 in opposition to thumb may discriminate the aperture evolution between collective fingers in palm opposition, collective fingers in pad opposition and independent finger movement in pad opposition.

Recent evidence by Castiello, Bennett and Stelmach (1993), showed a clear distinction between whether VF2 is mapped into one or more fingers in opposition to VF1 (as the thumb). Further, they demonstrated the importance of a natural mapping between object size and grasp. They compared blocked size and perturbed size conditions in which subjects grasped and lifted with natural grasps (i.e, VF2 mapped onto the index finger for a 0.7 cm diameter object, compared to VF2 mapped onto index, middle, ring and little fingers for an 8.0 cm diameter object) or with instructions for one of these grasps (called precision or whole hand grasps) for both small and large cylinders. Results indicated that with a natural grasp, there was little or no increase in movement time for selecting a new grasp type matched to the object size. In contrast, with instructed grasps, movement durations increased for adjustments of aperture to a size perturbation. Like Paulignan, Jeannerod, MacKenzie, and Marteniuk (1991), adjustments for perturbations from small to large were more difficult than from large to small. They also found that perturbations requiring a change from collective fingers to the index finger in opposition to the thumb (i.e., large to small perturbations) yielded a differentiable pattern in hand shaping (independent spatial path of the index finger from the others) about 173 ms after onset of perturbation of object size. Note that this time is substantially shorter than the 300 - 350 ms reported by Paulignan et al. for a readjustment to increase aperture between thumb and index (using pad opposition) with perturbation to object size.

Further research on the kinematics prior to contact is needed to understand how opposition space is set up with different types of oppositions. It is clear that the different opposition types show distinctive hand configurations (obviously!), as well as corresponding changes in the kinematics of transport. Following from the above research, more experiments are needed with a greater range of object properties and task requirements, as we discussed earlier in our analysis of different grasp types in Chapter 2.

5.4.4 Getting to grasp: Control by the CNS

Neural pathways controlling the proximal and distal muscle groups have a different organization. The proximal musculature used in reaching is controlled bilaterally by descending brain stem and corticospinal pathways (Brinkman & Kuypers, 1972; Lawrence & Kuypers, 1968a, b). Examinations of complete split brain monkeys demonstrated a clear dissociation between exclusively contralateral control of independent finger movements by the contralateral hemisphere, and bilateral control of more proximal reaching movements (Brinkman & Kuypers, 1972). In monkeys, cutting the pyramidal pathway does not affect reaching or collective finger movements to viewed objects, but does disrupt control of independent finger movements (Lawrence & Kuypers, 1968a, b). The independent finger movements required in pad opposition are controlled via the corticospinal tract in primates (Muir, 1985; Muir & Lemon, 1983; Tower, 1940). For palm opposition, or grasping with all the fingers flexing in unison to oppose the palm or palmar surface of the hand, the intact pyramidal system is not essential (Lawrence & Kuypers, 1968a, b). It may be that the brain stem pathways controlling collective finger movements do not provide the same sensitivity and refinement for motor control as the corticospinal system, nor the same fine calibration with visual information about intrinsic object properties such as size.

With respect to the motor cortex, we discussed earlier the work of Georgopoulos et al., who showed that a population vector representing the summation of directional preferences for individual neurons predicted well the direction of arm movements. Relevant to grasping is the finding that specific corticospinal neurons fire during performance of pad opposition (precision grip) between index finger and thumb, not during a palm opposition (power grip; Muir & Lemon, 1983). Using a cross correlational analysis between individual discharges of motor cortex neurons and the electromyograms (EMGs) of the contralateral intrinsic and extrinsic hand muscles, they identified a subpopulation of pyramidal tract neurons principally related to the small, intrinsic hand muscles[16]. These pyramidal tract neurons were active prior to contact and during the force applying phase of pad opposition. The motor cortex discharge in relation to forces produced

[16]Intrinsic hand muscles do not cross the wrist, i.e., their origins and insertions are in the hand. Appendix A provides figures to clarify.

and held after contact is examined in Chapter 6.

In premotor cortex, Area 6, a specific population of neurons (in subarea F5) showed discharge patterns specific to the shaping of the hand by monkeys in grasping (Rizzolatti, Camarda, Fogassi, Gentilucci, Luppino & Matelli, 1988). They identified whole hand prehension neurons (palm opposition), precision grip neurons (pad opposition) and finger prehension neurons. In an adjacent area (subarea F4), they describe populations of neurons that fired when monkeys were reaching to grasp visual objects. These two subareas were suggested to be related to the hand posturing and hand endpoint respectively.

An excellent review of cortical control of visually directed reaching and grasping is provided by Humphrey (1979). Figure 5.24 shows pathways of activity flow during visually and proprioceptively guided movements of the hand. Compared to control of the arm, the system controlling reaching and positioning of the hand includes other brain structures such as Brodmann's Areas 2 and 5 of the parietal cortex (Kalaska, Caminiti & Georgopoulos, 1983; Kalaska, 1988), and the cerebellum (Fortier, Kalaska & Smith, 1989). Movements of the hands and independent movements of the digits are effected chiefly through the descending corticospinal pathways from the motor cortex . Wrist and collective finger movements may also be produced through corticospinal projections from Area 5, or via corticorubral projections from Areas 4 and 5. Humphrey suggests that Area 4 effects hand movements mainly through three inputs:

1) central commands for manipulative hand movements coming in part from the intraparietal sulcus;
2) primary and association visual and somatosensory areas; and
3) <u>a gating or modulating input from the SMA</u>, in the presence of excitatory tactile or visual inputs, <u>until appropriate points in time during a movement sequence</u>.

Proprioceptive and tactile inputs to the motor cortex may be through the postcentral gyrus, and also through Area 5. The loop from Area 4 to cord to hand and back to Area 4 via postcentral gyrus or direct thalamocortical projections is identified as intimately involved in orienting grasping responses elicited by tactile stimulation of the arm or hand. Visual inputs to the motor cortex from visual association areas are by way of Areas 7, 8, posterior 9 and 6, and likely from Area 7 via Area 5 of the parietal cortex.

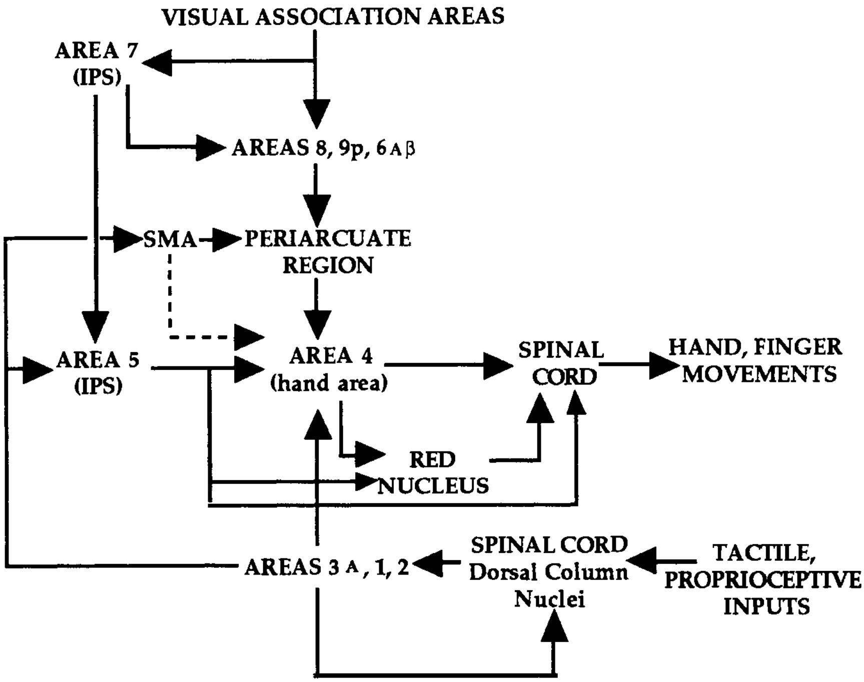

Figure 5.24 Hypothetical pathways of activity flow during visually and proprioceptively guided movements of the hand. Dashed line indicates inhibition of grasping or manipulative movements of the hand by the supplementary motor area (SMA) on primary motor cortex. IPS stand for intraparietal sulcus (from Humphrey, 1979; adapted by permission)

Jeannerod (1986) provides evidence that the formation of finger grip during prehension is a cortically mediated visuomotor pattern. Lesions of the posterior parietal area seem to disconnect independent finger movements from access to visual information. The posterior parietal areas (especially Area 7, within the inferior parietal lobule) have been implicated as key to the interactions and integration of visual and somatosensory inputs at the cortical level. Eye position information in Area 7 may combine with proprioceptive input about joint angles, muscle lengths and muscle contractile states, contributing to extrinsic-intrinsic transformations. This could give rise to population output signals from Area 7 varying with intrinsic coordinates, even if convergent inputs signal extrinsic information. Jeannerod (1986) provides a hypothesis that lesions in parietal Area 7 could disconnect visual and somatosensory information critical for patterning of visually goal-directed movements. It is assumed that this disconnection of visual and somatosensory information, and the associated distortions in sensorimotor transformations prevent alignment of the visual and proprioceptive maps of opposition space.

Somatosensory processing through the dorsal roots of the spinal cord is essential for grip formation, as has been demonstrated with deafferentations of the arm. Experimental monkeys with dorsal root sections show a corresponding loss of grip formation (Liu & Chambers, 1971; cited by Jeannerod, 1986). Dorsal column input has been implicated as essential for proprioceptive guidance of movements to achieve 'tactile foveation' in pad opposition. Glendinning and colleagues examined stumptail macaques (Macaca artoides) before and after lesions of the fasciculus cuneatus (Glendinning, Cooper, Vierck, & Leonard, 1992). For the first two weeks following surgery, monkeys neglected the affected hand, and did not use it for climbing, locomotion, support, foraging, scratching or grooming. Gross arm and finger movement returned gradually over the next few months, but the monkeys retained a 'wrist-drop' posture, with abduction and hypotonia of the fingers. They were unable to perform pad opposition in the same way postoperatively. Prior to surgery, the monkey approached small food objects with a highly consistent grip formation. The fingertips formed a small grip aperture during approach, and pad opposition between the index and thumb was obtained through a multiarticular pattern whereby the proximal joint flexed and the distal interphalangeal (DIP) joint of the index finger extended to align with the opposition vector, directly through the object into the thumb pad. Videotape analysis of kinematics, and grasp outcome postoperatively revealed alterations in grip formation: either excessive or not enough finger opening, with flexion about all joints of the fingers, a marked contrast to the DIP extension at contact preoperatively. All the monkeys used the table surface to help grasp items with fingers in opposition to the palm because they were unable to oppose the thumb and forefinger successfully. Vierck (1975, 1982) had earlier revealed permanent deficits in orientation of the hand during approach and grasp of an object using pad opposition, but had not captured the kinematic changes in grip formation. These results implicate kinesthetic sensory information in the planning and execution of grip formation, prior to tactile contact with the object.

For the interested reader, excellent reviews of the neural mechanisms in reaching and grasping are provided in the following books and papers: Goodwin and Darian-Smith (1985); Humphrey (1979); Hyvarinen (1982); and Phillips (1986).

5.4.5 Restricted sensory conditions

One way to gather information to answer the coupling question is to vary the available amount of sensory information, and see what the effects are on the various movement components. To recall, Wing et al. (1986) had subjects reach to grasp a vertically standing dowel under conditions where visual feedback and speed of movement varied. Focussing on the effects of the sensory manipulations, the peak grip aperture was larger in movements faster than normal and in movements where subjects had their eyes closed. There was more variability at peak aperture than at contact. At the frame just before contact (pre-contact), they noted more variability in the blind and fast conditions than in control conditions. This suggests the possibility of a very conservative Preshape controller, opening the hand wider when reliable visual information is not available. Recalling Jeannerod's experiments (1981, 1984), he noted that transport movements fell short of the target under conditions in which subjects saw only the objects, not the hand; in contrast, movements with vision had a longer MT and low-velocity phase. However, he did not observe a difference in maximum grip aperture and precontact grip aperture for the various visual manipulations.

While the importance of visual information has been demonstrated, the type and resolution of visual information can also have an effect. Normal vision is a combination of central vision (the central 10° of the visual field) and peripheral vision. Research has shown that central vision is functionally specialized for responding to spatial patterns, while peripheral vision responds to movement stimuli. In the Paillard (1982b) model seen in Chapter 3, it was suggested that movement and location cues from peripheral vision were used for transporting the arm, and size and shape cues from central vision were used for forming the hand. Interestingly, if the eyes are focused on the object, then at the end of the reach, both the object and the hand are in central vision.

Sivak (1989; Sivak & MacKenzie, 1990, 1992) performed manipulations of visual information in grasping tasks, using pad opposition. Infrared markers were placed on the wrist, index finger, and thumb in order to study the kinematics of the grasping and transport components using a WATSMART system. In the first experiment, a subject sat with the head stationary in a chin rest and was instructed to grasp and lift a vertically standing dowel (2.5 cm diameter, 11 cm high) placed on a table 30 cm in front of the start position of the hand, in the midline sagittal plane. In some of the trials, special contact lenses were worn that occluded the central 10° of visual field, confirmed with static perimetry (see Sivak, Sivak & MacKenzie, 1985, Sivak & MacKenzie, 1990). In these peripheral vision trials, the maximum grip aperture between the index finger and thumb was larger (116 mm) than with normal vision (86 mm), and occurred much earlier (see Figure 5.25). Individuals moved slower with peripheral vision only than normal vision. With normalization in time, the velocity profile of the wrist scaled similarly for both vision conditions, i.e., the same proportion of time was spent prior to and after peak velocity. However, a marked difference in the curves could be observed; the acceleration profiles showed that with peripheral vision, subjects decelerated, then appeared to maintain a near zero acceleration. Subsequent analyses revealed that, with peripheral vision, the forward movement of the arm toward the dowel stopped when approximately 72% of the movement duration was completed, in contrast to 91% for normal vision. When the wrist stopped moving forward, the aperture was larger for peripheral than normal vision. In effect, with only peripheral vision, the transport component seemed to have completed before the grasp component. Other kinematic analyses showed that with peripheral vision, subjects adopted a tactile control strategy whereby either the thumb or index finger made initial contact over 80 ms before lifting the dowel, perhaps to provide information and trigger the continued closing of the aperture.

To compare the sensitivity of central and peripheral vision for calibrating grasp aperture to object size, Sivak & MacKenzie (1992) had subjects perform the same grasp and lift movement but with dowels of 1.0, 2.5 or 5.5 cm in diameter. Seen in Figure 5.26, peripheral vision shows less sensitivity than normal vision in providing size information for calibrating the grip to object size. The obvious difference between the peripheral and normal visual conditions is the lack of visual acuity or high resolution vision with peripheral vision. Without high resolution information about intrinsic object characteristics (normally provided by central regions of the retina under natural viewing conditions), the aperture is much larger, and subjects adopt a tactile control strategy to acquire intrinsic object information, complete the aperture closure and actually grasp the object. Thus central visual information about object size obtained before and during the movement is critical for the planning and control of the grasp component. We suggested that the transport component was modified along with the grasp com-

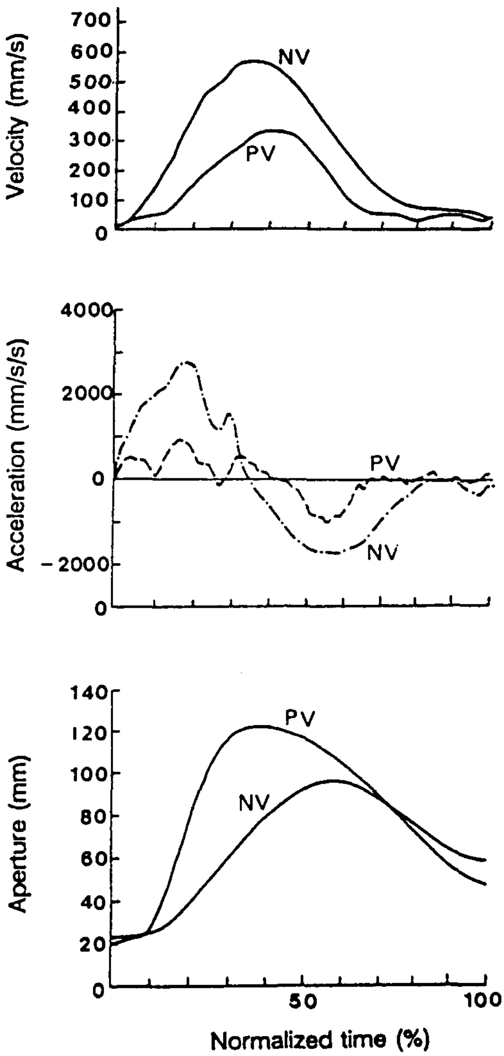

Figure 5.25 Kinematic profiles when grasping with pad opposition using normal vision (NV) or with vision restricted to the peripheral regions of the retina (PV) using specially designed contact lenses. In all cases, maximum aperture is greater when using peripheral vision than with normal vision. With peripheral vision, the arm had stopped moving forward as subjects enclosed the dowel and subjects adopted a tactile control strategy for completing the grasp, compared to normal vision. (from Sivak, 1989; reprinted by permission from Sivak & MacKenzie, 1992).

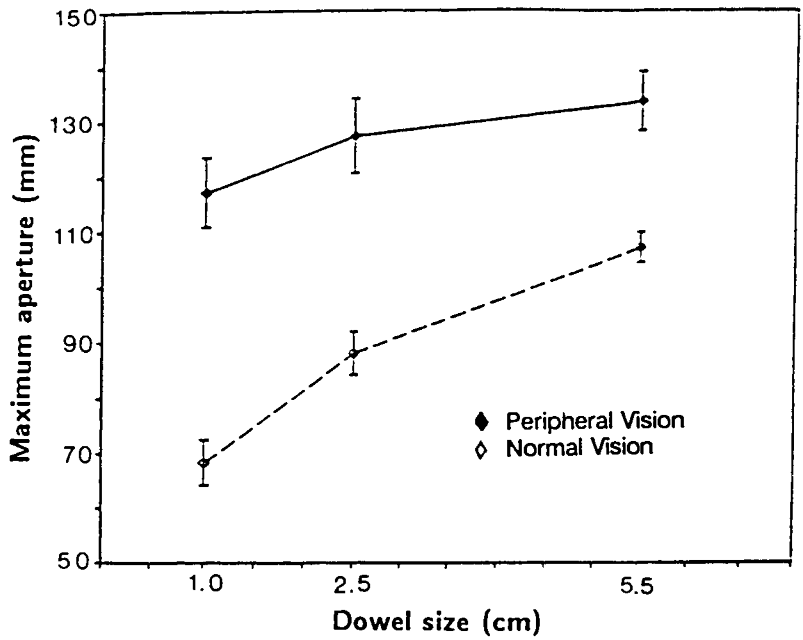

Figure 5.26 Maximum aperture as a function of dowel size (1.0, 2.5, and 5.5 cm in diameter) when grasping with pad opposition, using normal vision or with vision restricted to the peripheral regions of the retina using specially designed contact lenses. In all cases, maximum aperture is greater when using peripheral vision than with normal vision. Note the increased sensitivity of normal vision to object size, compared to grasping with peripheral vision only (from Sivak, 1989; reprinted by permission from Sivak & MacKenzie, 1992).

ponent as part of this control strategy, that is, there is a communication link between the visuomotor channels controlling grip formation and transport of the hand (Sivak & MacKenzie, 1990).

Sivak also compared central vision to normal vision (Sivak, 1989; Sivak & MacKenzie, 1992). Subjects wore goggles to allow vision in only the central 10° of the visual field. Using <u>central vision</u> alone, the parameters of the transport component were organized to suggest a nearer target than in reality. Subjects spent a greater proportion of time after peak deceleration with only central vision (52%), compared to <u>normal vision</u> (39%). Two distinct phases can be seen in the acceleration profile in Figure 5.27, suggesting subjects planned to stop the movement earlier than they did. When they did not contact the target,

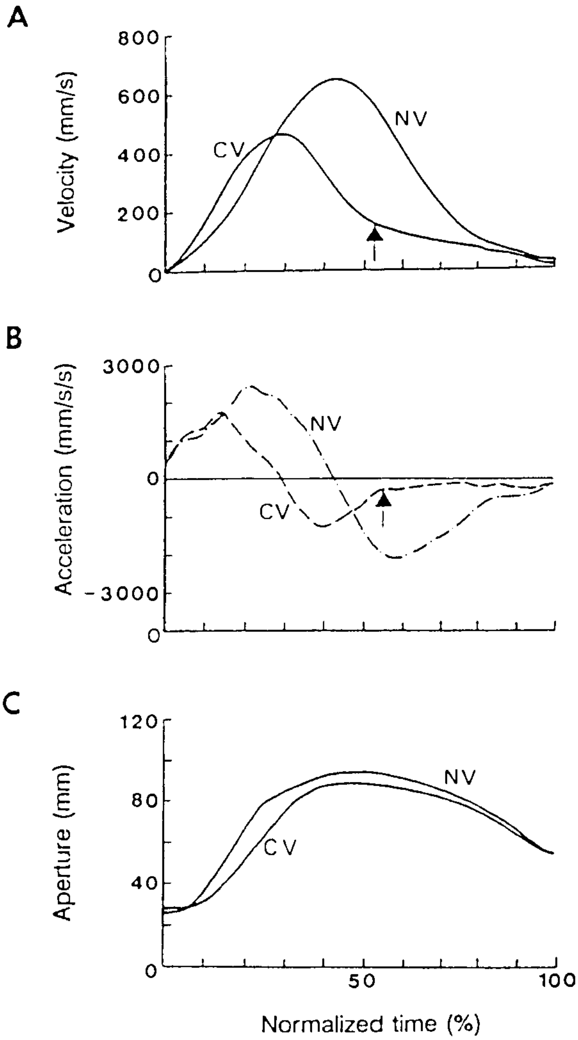

Figure 5.27 Kinematic profiles when grasping with pad opposition using normal vision (NV) or with with vision restricted to the central regions of the retina (CV) using specially designed goggles. A. Resultant velocity profile of the wrist marker B. Acceleration and C. Aperture beween the thumb and index fingernail markers. Note that with only central vision, there is absolutely no difference in aperture evolution compared to normal vision. In contrast, with central vision only, subjects seemed to underestimate the distance to the target (from Sivak, 1989; reprinted by permission from Sivak & MacKenzie, 1992).

they continued to decelerate at a constant rate until tactile contact was achieved. These were not submovements indicated by local changes in acceleration and deceleration, but a constant deceleration. Subsequent matching tests revealed that subjects could not estimate distance of the dowel accurately, thinking it to be closer than it was. Subjects did not adapt after practice. They had no difficulty determining the direction for the movement. Movement time was increased using only central vision following peak deceleration of the transport component. The acceleration profile of the transport seems to show two deceleration phases. In terms of the grasping component, in marked and reliable contrast to the effects on the transport component, the evolution of grip aperture was completely unaffected by restricting information to only central vision compared to normal vision. Central vision was also as sensitive to object size as normal vision, in terms of aperture profiles for grasping with pad opposition. Thus peripheral vision does not appear to be necessary for planning and control of the grasp component (Sivak & MacKenzie, 1990).

The major difference between the central and normal visual conditions was the small field of view with only central vision. The small field size reduced the amount or quality of dowel location information, and on line visual feedback information about the moving limb. Although it has been suggested that peripheral vision is used to provide information necessary for directing the limb to the proper location of an object (Bard, Hay & Fleury, 1985; Paillard, 1982b; Paillard & Amblard, 1985), subjects in the present experiment had no difficulty with the direction, only the distance of the movement in the absence of peripheral vision[17]. In the absence of peripheral vision, eye and head position (and the motor control process of foveation) may provide sufficient information about the direction of an object to be grasped. Replicating others, the results from this study suggest that direction and distance are separable control parameters for location of an object (Sivak, 1989; Sivak & MacKenzie 1990).

The roles of central and peripheral vision in visuomotor integration processes are suggested to be as follows for grasping under normal viewing conditions. Peripheral vision provides important information about the distance of an object (Sivak & MacKenzie, 1990), direction (Bard, Hay & Fleury, 1985), and information about object or limb motion (Bard et al., 1985; Paillard, 1982b). As suggested by Paillard

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[17] Since this experiment required only one direction to move, i.e., in the midline plane, it is not clear whether peripheral vision was necessary to assess the direction of movement.

(1982b), this information appears to selectively contribute to the planning and control of transport of the hand to the object, not to the formation of the grip. Under natural viewing, central vision provides important information about object size (and possibly other intrinsic object characteristics), for accurate grip calibration and hand posturing in opposition space[18]. This objective object size information contributes to the organization and control of both the grasp and transport components. Without the high resolution provided by central vision, subjects adopt a tactile control strategy, increasing the length of time they are in contact with the object, in order to successfully complete the grasp.

Accurate distance information appears to be provided by binocular vision; with only monocular viewing, subjects appeared to underestimate the distance to objects, as well as their size (Servos, Goodale & Jakobson, 1992). Combining three oblong object sizes with three movement distances, they found that when viewing the objects monocularly (with the preferred eye), movement times were slower, peak velocities and accelerations were lower than with binocular vision. As well, greater time was spent in the deceleration phase after peak velocity with only monocular vision (583 ms or 69%), compared to binocular vision (390 ms or 63%). These viewing effects interacted with object distance on kinematic peaks, e.g., the effects of distance on peak velocity replicated earlier work but were attenuated in the monocular viewing condition. Subjects always had a smaller peak aperture under monocular viewing conditions (84 mm) compared to binocular ones (90 mm). Thus, it appeared that subjects were underestimating both the distance and the size of the objects. With both monocular and binocular viewing, the maximum aperture showed a similar calibration to visually observed intrinsic properties (i.e., slopes of the function relating maximum aperture to object size were not provided, but appear similar, even though with monocular vision, maximum aperture was consistently smaller). Although not mentioned, it is assumed that under all conditions, subjects accurately

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18 Sivak & MacKenzie (1992) noted with interest neurodevelopmental differences between central and peripheral regions of the retina. The retina is fully developed at birth except for the foveal area which is not completely functional until about 6 months of age. This is about the same time at which pad opposition emerges in infancy (see von Hofsten & Ronnqvist, 1988). Neural, behavioral and functional parallels in foveal development for foveal grasping and the development of the somesthetic macula of the finger pads for pad opposition is an intriguing area for further exploration.

calibrate the hand opening at contact to successfully grasp the object. Under both binocular and monocular viewing conditions, the objects could be seen in foveal vision. Recall that with only central vision, Sivak also found that subjects underestimated the distance to objects, but calibrated the grip to the size of the object, in exactly the same way as with normal, binocular vision (Sivak, 1989; Sivak & MacKenzie, 1992).

Evidence indicates that some sort of proprioceptive information is also crucial to the preshaping of the hand. For patients having no sensory information from the periphery (from tactile, muscle, joint and tendon receptors) or having lesions in the parietal cortex, preshaping of the hand could only be accomplished with vision (Jeannerod, 1986). Jeannerod studied a patient who lost all sensation on her right side due to the blood flow being blocked to her left anterior parietal cortex (patient 6, R.S. in Jeannerod, 1986). As seen on the left of Figure 5.28, she could preshape her normal left hand as she reached out to grasp the object under visual control. The center column of the figure shows her affected right hand doing the same task, much slower, and with more corrections under visually guided control. She could preshape the hand, but only when the hand was within her eyesight. On the right side of the figure, it is shown that she had no ability to preshape the hand without visual feedback. It appears that with interruption of the somatosensory pathways, subjects need visual information in order to configure the hand. Without visual infomation, the affected hand cannot be preshaped, and the transport component is also affected.

In addition to lesions in central pathways, disruptions in peripheral pathways can lead to impaired motor performance. In Rothwell et al. (1982), a patient known as G.O. lost light touch, vibration and proprioceptive sensation due to a sensory peripheral neuropathy[19]. He was able to perform a variety of tasks, such as thumb positioning and drawing figures in air with his index finger. Kinematic measures of his performance in thumb positioning tasks requiring fast and accurate movements were similar to those of normal subjects. On the slower movements, he exhibited more variability and less accuracy than normal subjects, and clearly demonstrated his reliance on vision. Interestingly, while the subject was able to perform well in laboratory tests, his need to constantly monitor his movements by vision severely limited his hand usage in his daily living. Without proprioceptive information for sustained contractions of muscles, he had lost the

[19]A disorder in the peripheral nerves.

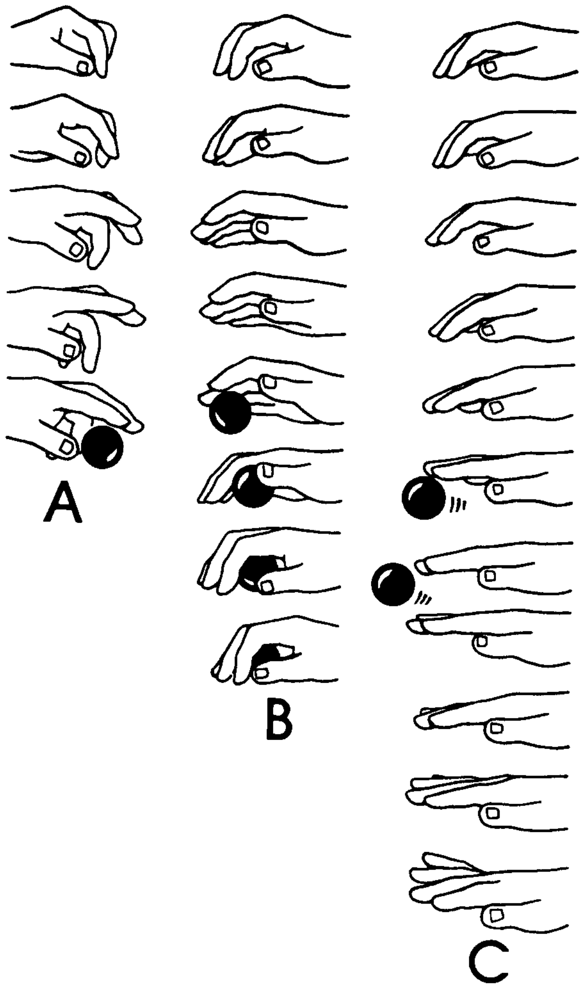

Figure 5.28 Without visual or kinesthetic sensory feedback, this patient cannot preshape her hand. The lesion was in the anterior part of the left parietal lobe (somatosensory strip). The motor cortex was spared. (a) Normal hand reaching to grasp object. (b) Affected hand with available visual information after the line. (c) Affected hand without visual information (from Jeannerod, 1986; reprinted by permission)

ability to maintain a constant motor output or sustain movements over several seconds without constant visual monitoring.

5.5 Schemas for Setting up an Opposition Space

Modelling the reaching and grasping schemas in the CCP can be done by focusing on what is the problem each schema is trying to solve and what type of data are perceptual schemas providing. An important point identified in the previous section is that preshaping the hand seems to be fundamentally different than enclosing the hand around the object. A secondary point, that necessarily follows from this, is that the arm slows down in order to effect this enclosing process. In this section, various models are explored that might account for this phenomenon. In addition, an analysis of preshaping vs enclosing is presented, with terminology from the robotics community used to introduce the enclosing process as a guarded motion.

5.5.1 Getting in the ballpark: Move$_{fast}$ and Move$_{slow}$ schemas

In all the studies of grasping kinematics, one consistent finding is that the movement has two distinct phases, a fast phase getting the hand near the object, and a slower, final adjustment phase. If there are indeed two phases of movement (some argue more: e.g. Crossman & Goodeve, 1983; Milner & Ijaz, 1990; some argue less: e.g., Hoff & Arbib, in press), what might be the reason? It is not necessarily for visual error-correcting, since Jeannerod (1984) and many other researchers showed that the second phase occurs with and without visual feedback. Arbib, Iberall, & Lyons (1985) suggested that the initial phase of reaching could be the result of a plan to first put the arm into the 'ballpark' of the final goal and then the second phase to ensure contact. Suppose, in a slightly different context, one must place a mug on a table (see Figure 5.29a). The mug is brought towards a target location A on the table during a fast movement, with the goal of the movement actually slightly above A; that is, $A+\partial_1$. As the mug is lowered onto the table during a slower movement, the goal is actually inside the table; that is, $A-\partial_2$. The environment stops this from occurring, of course, thus stopping the mug from actually going through the table. This second movement must be relatively slower than the first, otherwise, something (maybe fingers!) is in danger of breaking. For control, a generalization using two interacting schemas is seen in Figure 5.29b. The first schema generates a movement to a location nearby the target, the second generates a movement through the target. Arbib and colleagues note the advantage of assuming a small buffer factor $\pm\partial$ for movements involving contact with objects.

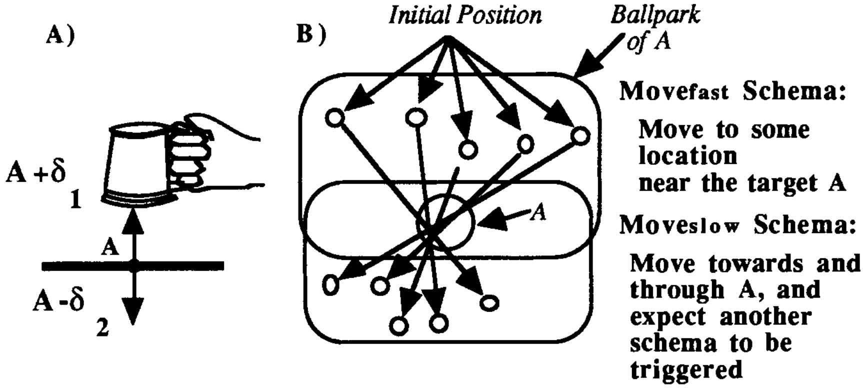

Figure 5.29 Arbib, Iberall, Lyons (1985) notion of 'ballpark'. A) Placing a mug on a table involves getting the mug to a location above the target location, and then moving the mug through the target location (i.e., through the table), resulting in sensory contact triggering other schemas. B) Generalization of the ballpark model showing how two Move Schemas work together.

For the first phase of a movement, adding ∂_1 to the goal position A , would prevent accidental contact with the object; for the second phase of a movement, subtracting ∂_2 would ensure contact, as the goal of the movement would actually be inside the object. In this way, uncertainty can be dealt with in perceptual data.

These reaching schemas can be modelled using neural networks in terms of ballpark modelling. Recalling the Coordinated Control Program (Figure 5.1), the hand is moved by the Move$_{fast}$ Schema from a given starting location and posture to be within the ballpark of a desired location. The Preshape Schema shapes the virtual fingers into a posture larger than the object at peak aperture. Then, the Move$_{slow}$ Arm Schema moves the wrist beyond the desired location. The Enclose Schema brings the virtual fingers together, bringing the fingers 'into' the object (of course, the object surfaces stop the fingers at the appropriate time). The Approach Vector Selector model, described in Chapter 4, provides one method for computing a goal hand location (Iberall, 1987a). This 'winner take all' non-adaptive framework computed a good location for contacting a 4 cm dowel with two virtual fingers in pad opposition. A good location for the hand is one where the VFs could reach the ends of the dowel, and where the pads are aligned with each other as well as with the dowel. Following the ballpark concept, the $Move_{fast}$ Schema does not have to put the hand at this location; instead, it puts the hand within the vicinity of this location. The actual mechanism for driving the hand can be done using one of the models described in this chapter, such as the VITE model (Bullock & Grossberg, 1989) or Jordan's inverse kinematic model (Jordan, 1988).

One question is what is the right ballpark, or, more formally, what is the size of the buffer ∂_1? A pilot study, where one subject was asked to pick up a light, horizontally resting wooden dowel between his thumb and index finger pad, offers some evidence (Iberall, 1987a; Iberall & MacKenzie, 1988). Measurements were taken of virtual finger lengths and angles at the beginning of the movement, at the time of the peak aperture between thumb and index finger, and at the time when the dowel was grasped. For differing dowel orientations, the results showed that VF1 and VF2 parameters at peak aperture were within the ballpark of their values at contact, but there seemed to be tighter constraints on VF1 than on VF2 at peak aperture. This supports the view that the thumb moves less than the index finger (Wing & Fraser, 1983, Wing et al., 1986).

In terms of the use of sensory information, it was noted that when subjects are deprived of visual feedback or do not have enough time to process it, more errors are made and larger peak apertures are formed. This suggests a larger 'ballpark'. With a larger initial buffer factor, the subjects avoid accidental contact, which is more likely to occur when visual information is not available or there is not enough time to update one's internal model, as was observed by (Wing et al, 1986). From the reaching perspective (the transport component), a two phase movement helps to ensure success despite perceptual errors in locating the object. In terms of grasping an object (the grasping component), a two phase movement with ballpark positioning of the fingers allows errors in perceiving object characteristics such as shape.

Other models of the preshaping and enclosing phases have been suggested. In reevaluating the CCP, Hoff and Arbib (in press) developed a new model that used expected duration for the coordination of the preshaping and enclosing schemas. Noting that the time it takes to enclose the hand seems to be invariant in perturbation studies, about 200 ms (Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991; Gentilucci et al., 1992), Hoff and Arbib call the model the Constant Enclose Time model (see Figure 5.30). The Transport Arm Schema takes as input the target distance and it computes how much it needs. At the same time, the Preshape Schema re-

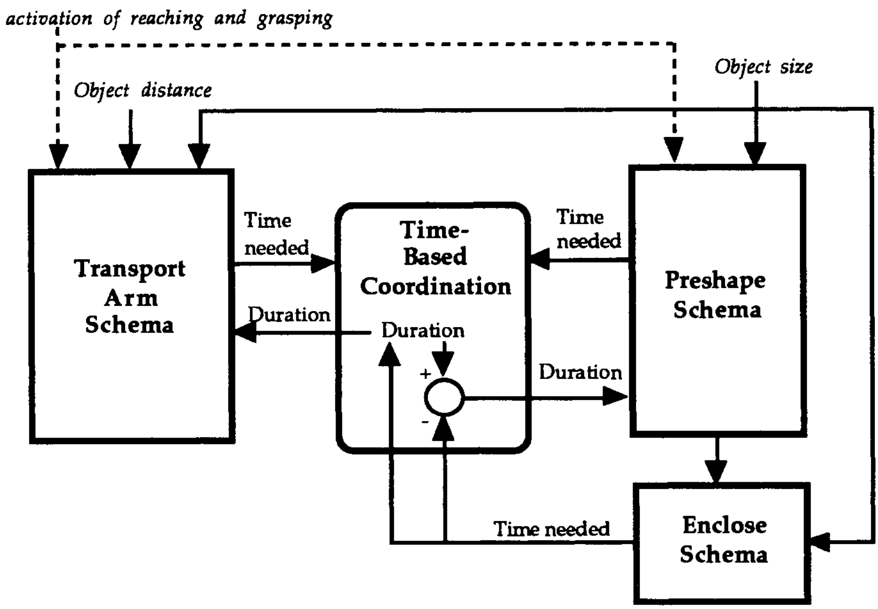

Figure 5.30 Hoff and Arbib updated schema model for preshaping and enclosing. Extrinsic object properties (distance) are sent to the Transport Arm Schema, while intrinsic ones are sent to the Preshape Schema. Both compute the length of time needed for the action. The Time-Based Coordination Schema determines which is maximum and sends the planned duration back to both. Enclose Time is subtracted from the value sent to the Preshape Schema. The hand will then be preshaped prior to arrival of the hand at the object with enough time to enclose the fingers around the object (from Hoff & Arbib, in press; adapted by permission).

ceives the object size, computing how much time it, along with an added constant enclose time, needs as well. The Time-based Coordinator receives these Time Needed values and compares them, finding the maximum. This value is then sent back to the Transport and Preshape Schemas as planning duration, subtracting the Enclose Time from the value it sends to the Preshape Schema. This scales the preshaping and transport in time. The hand will always reach its peak aperture prior to arrival of the hand at the object, with just enough time to enclose the hand. Computer simulations of this model were performed, with results mirroring the experimental data of Jeannerod (1981) and of Paulignan, Jeannerod, MacKenzie, and Marteniuk

(1991) and Paulignan, MacKenzie, Marteniuk, and Jeannerod (1991). This includes the bell-shaped velocity profiles and the occurrence of a peak aperture. Prolonged deceleration is seen when target location is perturbed, and two peaks in grip aperture are observed. When object size decreases, the aperture levels out before proceeding to the new maximum.

Following Jeannerod's hypothesis that these two components are linked in time, the Hoff and Arbib model is a powerful model. It is useful for making predictions. Hoff and Arbib predict that grasping nearby objects, with a tight time constraint, will lead to low velocity profiles, since there is a lower bound on the movement time. The model seems to work for perturbation data, but have limited generality since constant enclose time was not found in many studies, for example, Marteniuk et al. (1990) where disk diameter varied. As disk size decreased, the movement time increased and the time after peak aperture increased.

5.5.2 Enclosing as guarded motion

An argument can be made that preshaping (up to the time of maximum aperture) and enclosing (from maximum aperture until contact) are uniquely different movements. While both are free motions (no interaction with the environment), two fundamentally different things are happening. During preshaping, the hand is opening up and there is a desire to avoid contacting anything in the environment until this is complete. In terms of a controller, if the free motion is ballistic, then contact is of course ignored. But after the previously unrestrained movements of preshaping, during enclosing, there is anticipation of the upcoming compliant motions to be made during contact with the object. During enclose, the hand is trying to establish tactile contact, whereas in the preshaping phase, contact was being avoided. In robotics terms, this enclosing motion would be called a guarded motion. During a guarded motion, sensory information is sought, whereas in unrestrained movements, contact with the environment is avoided. In fact, if human prehensile motions were planned in terms of sensory consequences, then the CNS might compare the anticipated tactile feedback to the current tactile information. During preshaping, there would be no anticipated tactile feedback, and during enclosing, there would be a tactile or haptic pattern anticipated on the palmar pads as determined by the chosen posture and object characteristics such as shape, size, texture, etc[20].

Another way to distinguish a preshaping phase from an enclosing phase is to look at what occurs at the muscle level. Smith et al. (1983) used electromyographic (EMG) data, to study muscle activation in primate pinching movements between thumb and index finger in side opposition[21]. As seen in Figure 5.31, the extensor digitorum communis (EDC) muscle activates at around 300 ms before the onset of force, extending the fingers as the hand opens prior to grasp. The abductor pollicis longus (ABPL) acts next, at -220 ms, extending the thumb, while the lumbricals (LUMB) at -200 ms aid in extending the fingers. The enclosing phase begins with the thumb muscles, the opponens at -100 ms (OPP), then the flexor pollicis brevis at -90 ms (FPB) and abductor pollicis brevis at -40 ms (ABPB) to flex the thumb, and adductor pollicis at -30 ms (ADP). The extensor pollicis longus at -20 ms (EPL) extends the thumb toward the radial side of the hand for the side opposition. The fingers are adjusted by action of the first dorsal interosseus, which also acts on the thumb, at -20 ms (INTD 1). The flexor digitorum profundus activates at 0 ms (FDP) to apply the actual force. The onset of contraction of both adductor pollicis and flexor pollis brevis are time locked to the onset of force, suggesting that these two muscles function as prime movers in this isometric precision grip. The extrinsic (FDP, FDS, FPB, FPL) and intrinsic flexors (INTD 1, LUMB, ABPB) are activated at force onset, where FDS is the flexor digitorum superficialis and FPL is the flexor pollicis longus.

In order to grasp an object, it is necessary to set up the relevant force-producing muscles for the anticipated interaction. Smith et al. (1983, p. 376) argued that the early onset of the EDC may function to

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[20]Supporting data has been found in the hand representation of somatosensory cortex. Iwamura and Tanaka (1978) found neurons responding in Area 2 to particular object features, such as cylinders or flat objects. Hyvarinen and Poranen (1978) found other neurons in the same area responding to direction of movement across the palm. Other neural evidence for the difference can be seen in the ablation of area 5 causing tactile avoidance, and ablation of SMA causing tactile following (the release of instinctive grasp reflex). Perhaps SMA inhibits the enclosing until the preshape has been formed.

[21]While the muscles of other primates and their action are slightly different from ours, the reader is encouraged to see Appendix A for a list of muscles.

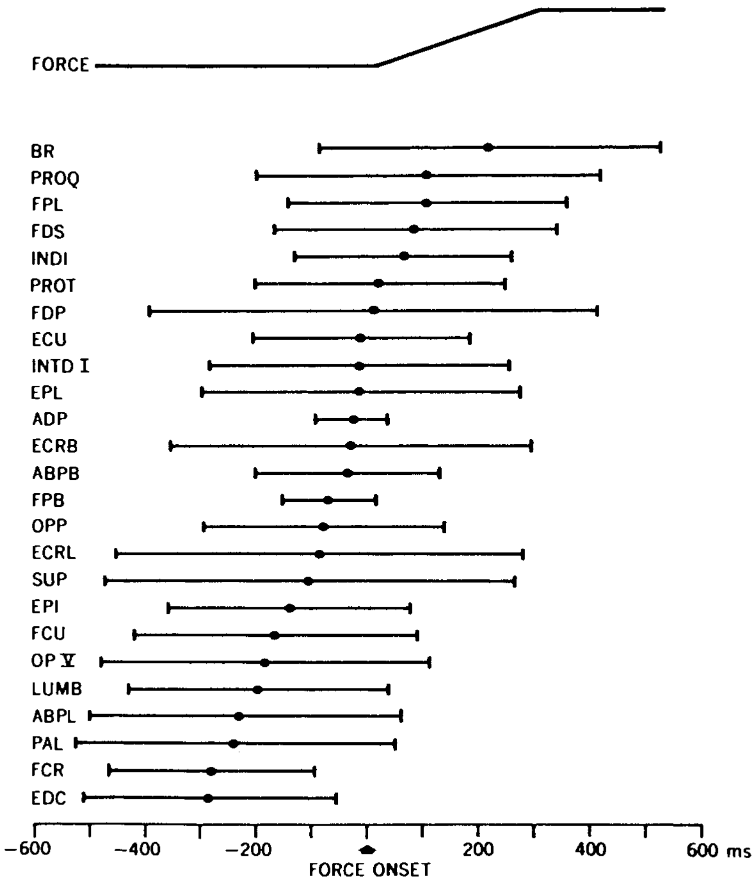

Figure 5.31. EMG activity from muscles in the forearm as fingers first open and then pinch an object. Some act to preshape the hand, others to close the fingers (from Smith et al., 1983; reprinted by permission).

> "...stretch the long finger flexors before their contraction in order to increase prehensile force and may be somewhat similar to the crouching that precedes jumping and wide jaw opening prior to hard biting..."

Using this as a model then, we can hypothesize what might be occurring. During preshape, the force production muscles are stretched. At the start of the enclosing phase, they become active to perform their first function: that of 'closing the fingers' around the object. On contact, they begin their second function, that of 'generating the forces' against the object. An important correlative study to Smith's work would be to look at how these force producers are brought into position; i.e., look backwards from contact through enclose through preshape. At some moment in time, the goal of the movements shifts from 'closing' to 'generating force', and it would be interesting to observe this both behaviorally (at peak aperture) and at the EMG level.

In this regard, it is of import that the lumbricals (intrinsic hand muscles, which serve to flex the metacarpophalangeal joints of the fingers, but extend the interphalangeal joint; see Appendix A) have their origins on the four flexor profundus tendons on the palm. They have been suggested to have an important sensory function, that of monitoring the rate of finger flexion, or enclosing of the hand during grasping (Ranney & Wells, 1988). Combined with the myriad of other sensory information in the multiarticulate hand, the guarded motion phase should be uniquely detected, and anticipatory of the force production once contact is made.

5.5.3 Palm-focused model of grasping

The hypothesis that both reaching and grasping movements are two-phased sets up the question of what is the relationship between the $\text{Move}_{\text{slow}}$ Schema and the Enclose Schema. There has been no correlation between the start of the slow phase of the arm movement with the start of the finger enclosing. However, noting that the arm acts differently when doing simple tasks than when reaching to grasp, a new model is offered in Figure 5.32. This model focuses on what the palm is doing during prehension. Instead of the wrist, the palm is the interface between the transport component and the grasping component. Palm orientation is resulting from wrist flexion/extension, ulnar/radial deviation, pronation/supination, elbow flexion/extension, shoulder flexion/extension, abduction/adduction, internal/external rotation and pectoral girdle upward/downward rotation, elevation/depression, and protraction/retraction. Note that most of the muscles involved in transporting the arm are involved also in orienting the palm and thus the fingers; for example, the primary action of the biceps is to flex the elbow, but the biceps is also a supinator of the forearm. On the left side of the figure, the Orient Palm Schema transports and aligns the palm (in contrast to the wrist) relative to the opposition vector seen in the object. On the right side, the Preshape

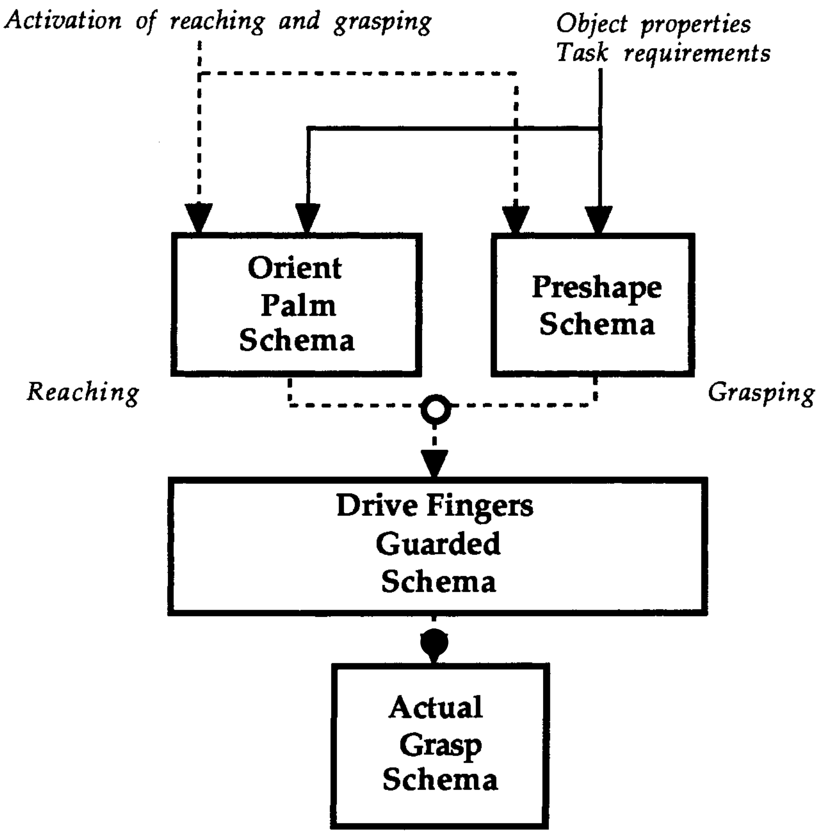

Figure 5.32 Palm-focused model of setting up opposition space for prehension. During activation of the Orient Palm Schema, reaching movements orient the palm and position it close to the object. In parallel, the Preshape Schema shapes the fingers into a posture suitable for that palm alignment. When preshaped, positioned, and oriented, the Drive Fingers Guarded Schema is activated in order to drive the arm, wrist, and hand in a direction to make contact with the object. Since it is a guarded movement, contact with the object will stop the schema, and activate the Actual Grasp Schema.

Schema configures the fingers into a posture suitable for that palm alignment. The hand configuration is computed in a palm-centered coordinate system.

In comparison to the CCP, the Orient Palm Schema in Figure 5.32

collapses the CCP's 'ballistic movement' schema (or $\text{Move}_{\text{fast}}$ Schema) and 'hand rotation' schema. The Orient Palm Schema generates necessary commands for the six spatial degrees of freedom specifying the position and orientation of the palm. Importantly, the Drive Fingers Guarded Schema encloses the fingers around the object which entails motor commands to the fingers, palm, wrist, and arm. The Drive Fingers Guarded Schema replaces the CCP's 'adjustment' (or $\text{Move}_{\text{slow}}$ Schema) and differentiates the enclose action from the preshape action in the 'finger adjustment' schema. During the activation of the Drive Fingers Guarded Schema, guarded movements of the fingers, palm, wrist, arm and pectoral girdle bring the fingers into contact with the object. Fine adjustments at all joints can be used for final alignment of the contacting hand surfaces with the opposition vector(s) seen in the object. This guarded move, programmed in terms of sensory consequences, activates the Actual Grasp Schema at contact. The Actual Grasp Schema is detailed in Chapter 6.

In Figure 5.33, the behavior of the palm-centered model can be observed. The Orient Palm Schema is used to position and orient the palm in Figure 5.33b within some ballpark on a desired palm position and orientation. At the same time, the Preshape Schema opens the fingers into some virtual finger configuration within the ballpark of the desired VF configuration. In Figure 5.33c, the Drive Fingers Guarded Schema closes the fingers into the object and brings the palm in closer. The goal driving the finger trajectories (and the arm) is the alignment of the grasping surface patches of the hand with the seen opposition vector, given the opposition space parameterization appropriate for the task. Actual contact stops the fingers and arm.

In summary, the palm-focused model suggests that the palm is the interface between the hand and the arm, not the wrist. During the first phase of the movement, the focus is to align the palm to the object. In parallel, the fingers open or close into a posture based on that palm alignment. During the second phase of the movement, the focus is to make contact with the object, thus enslaving the arm to the hand.

5.6 Summary of Setting up an Opposition Space

The black box introduced in Chapter 1 mapping object and task characteristics to prehensile behaviors can be looked at in terms of observable kinematic features (see Figure 5.34). From the work cited in Chapter 4 and also here, we extend the description of objects to have both intrinsic and extrinsic properties. Intrinsic properties include surface spatial density, fragility, weight, size, shape, center of

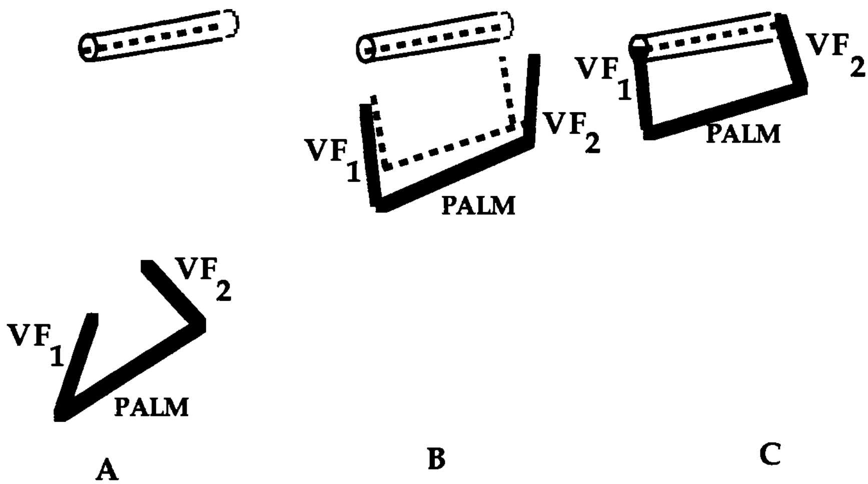

Figure 5.33 The behavior of the palm-focused model of setting up opposition space for prehension. The dashed line along the long axis of the object shows the opposition vector perceived in the object. The solid lines show the hand configuration for pad opposition, where VF1 is the thumb and VF2 is the one or more fingers in opposition. Starting at an initial posture and hand location (A), the palm is positioned and oriented and fingers shaped into some ballpark of the desired location and posture, shown in dashed lines (B). Then, while the arm makes necessary fine adjustments to align the palm, the fingers close trying to go into the object, but are stopped by actual contact (C).

mass, and distribution of mass. Since behavioral experiments define the task as the environmentally defined task, we list tasks used in the experiments, such as 'aim', 'fit', 'grasp', 'place', etc. Observable kinematic features of prehensile behaviors come from the transport component and from the grasp component. From the transport component, movement time, wrist velocity, acceleration, and even jerk have been measured. For these, peaks and time to and after peaks have been used to help identify potential control variables. In terms of the grasp configuration, the aperture between thumb and index finger has been a critical metric of prehension, while also joint angles have also been measured.

Even from common everyday experiences, it can be seen that hands preshape into some suitable posture as reaching to grasp objects occurs. Teasing apart the reasons for how and why these unrestrained

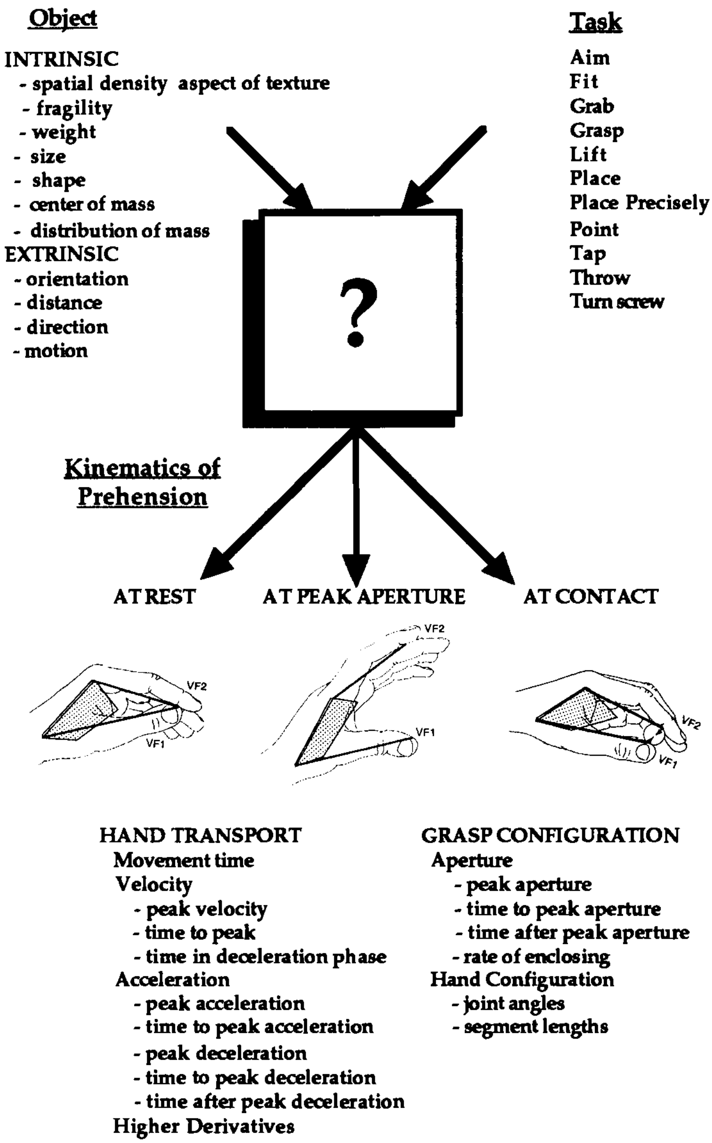

Figure 5.34 The black box revisited. Objects have intrinsic and also extrinsic properties. At the environmentally-defined level, tasks include grasp, lift, and place. At the kinematic level, prehensile behavior can be measured by movement time, velocity, acceleration, etc. For grip evaluating, a key metric has been the grip aperture, or the thumb and index finger separation over time.

movements occur is a complex problem. The constraints acting on this behavior, ranging from the availability and use of sensory information, the way movement can be generated by our muscles, the activation and subsequent use of force generating muscles for compliant motion, all combine to produce complex interactions between the behavior of the transport component and the grasping component of prehension. Research has suggested a coupling between these two components, indicating that the way the arm behaves alone (as in pointing movements) is different from the way the arm works when the hand is involved (as in reaching and grasping movements). For example, Jeannerod (1984) proposed a temporal coupling, while Wing et al. (1986) argued for a spatial coupling.

Movements that involve an interaction with the environment seem to be different than movements that don't. Fitts' law, one of the few lawful relationships in motor control, demonstrates a speed-accuracy tradeoff. Extending Fitts' Law, MacKenzie et al. (1987) showed that asymmetric velocity profiles point to the possibility of a two-phase controller for complex movements where interaction with the environment is required. Questions have been raised regarding the relationship between movement duration, distance, velocity, and acceleration. Some invariances have been identified. In terms of how people interact with objects, the environmentally-defined goal seems to affect the motor control as well, suggesting that a precision effect might be in play when performers interact with the environment. This precision effect, as described by Marteniuk et al. (1987), shows up in the second part of the movement where sensory information is needed for changing from an unrestrained movement to a guarded and compliant movement. An important point is the question dealing with the type of sensory information needed for visually-guiding the arm. As Wing et al. (1986) suggested, very little sensory information may be needed, if the correct information is available (e.g., if vision of the thumb or finger is not occluded at a crucial time in its trajectory). Finally, an important question is the differential influence of intrinsic and extrinsic object properties on the arm (the transport component) and the hand (the grasping or effecting component). Ultimately, answers to this question will relate back to Fitts' Law and the use and need of sensory information in a motor task.

In terms of visual information needed in a task, movement components are affected when no visual information is available. Lacking visual feedback, accuracy is decreased and movements are more conservative (e.g., grip aperture opens wider), as shown by Wing et al. (1986), among others. While the notion of two-phase movements might be due to visual feedback correction during the second phase, the second phase exists in conditions where vision is lacking, arguing against the notion that the second phase is due to the need for visual feedback corrections. Importantly, however, when visual information is available (or possibly available), it will be used. With vision, movements are longer. Finally, an important issue is the distinction between the use of peripheral and central vision. According to Sivak and MacKenzie (1992), when only peripheral vision is available, both the grasping component and transport components are affected. Movements are slower and location is more uncertain, when the temporal link is broken between transport and grasping.

Two major goals seem to be at work, which in their own way influence both the arm and the hand. Firstly, perception of the location of the object influences movement parameters; uncertainty in object location dictates slowing down in the vicinity of the object, particularly if the objective is not to bowl it over or crush it. This affects both the transport component (change in velocity profile) and the grasping component (open hand before contact is anticipated). Secondly, perception of force-related object properties (e.g., weight, surface texture, surface sizes) and goals for task performance (e.g., direction and type of motions to impart, forces to apply) affect the transport component (kinematic and kinetic effects effects) and the grasping component (posturing force generation muscles for the task).

Various models have been proposed for trajectory planning. Bullock and Grossberg (1989) used an internal model of muscle length in their VITE model and a time-varying GO signal to update the model. Kawato et al. (1987) suggested a model for combining three controllers: a slow cortical feedback controller, a faster cerebellar feedback controller, and a even faster cerebellar feedforward controller. Jordan (1988) designed a two tiered network for first learning the forward kinematics of an arm and then learning sequences of movements. Constraints were identified to smooth out the movements and solve ill-posed problems. Massone and Bizzi (1989) used the Jordan network to generate trajectories of muscle activations. Instead of derived constraints, they minimized a potential-energy cost function in order to generate unique solutions.

The CNS may be trying to get some parameters into the 'right ballpark' which can then be fine tuned. Prehensile planning can be performed by a network of 'neuron-like' processes working together to compute a desired posture and position and orientation from estimated object location, orientation, and size. These desired values can then generalized into some ballpark for performing the first phase of the movement. It is suggested here that orienting and positioning the palm seems to be crucial to prehension. From the reaching perspective, the arm muscles get the palm into a ballpark of its final location. From a grasping perspective, the fingers can preshape into a suitable posture, based on the assumption that the palm will be aligned correctly. Fine tuning can then occur during the second phase of the movement, where the orientation of the palm is fine-tuned by wrist, elbow, and shoulder muscles, while the fingers close in around the object. Feedback mechanisms can then overcome errors in perception during this second phase of the movement.

The level of the motor command is uncertain. Models have suggested how it occurs at the joint angle level, joint torque level, and muscle level. When starting from a goal location specified in a world or body coordinate frame, an important computation is to transform that goal into one of these motor levels. Computations may proceed in an orderly fashion (Step 1 --> Step 2 --> Step 3) as Uno et al. (1989) outlined. From a biological perspective, this is inefficient. Alternatives are to compute motor commands more directly (Steps 4 or 5) or also to plan in joint space (Step 1'). Whether the computation is inverse kinematics or inverse dynamics, it is an ill-posed problem. Cost functions and/or constraint satisfaction networks suggest ways to limit the computation towards selecting a unique solution. Of course, the CNS never seems to have a unique solution, evidenced by the issue of motor equivalence and also of the exhibited variability. Thinking about the sensory side as a distributed representation (e.g., combining two dimensional with three dimensional information and perhaps even velocity cues, etc.) may shed light on the motor side: it too could be a distributed computation involving many levels of sensory reprentations and motor commands. Arbib's coordinated control program is a first step in this direction.

The CNS allows parallel and redundant processing of sensory information for motor control. While sensory information (given a modality and sub-modality as well) is needed at crucial times for completion of a motor task, there are many ways that it can solve problems. In the 1990s, it is still not possible to distinguish the kinematic features in reaching and grasping movements attibutable to supraspinal planning processes, spinal circuitry or the inevitable consequence of musculoskeletal mechanics. The CNS seems to find simple solutions out of its multi-faceted repertoire of possible modes of interacting with the environment.

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Chapter 6. During Contact

"And finally, the act of grasping an object includes more than the accurate direction of the movement on to the target: the pressure of the grasp must neither crush an egg nor allow it to slip from the fingers."

-- C. G. Phillips (1986, p. 6)

After initial contact, the hand captures the hammer, establishing a stable grasp. The hand must maintain this stable grasp. Otherwise, the object will fall out of the hand. Of course, as Fearing (1986) noted, skills such as baton twirling go beyond this restriction. Here, the skill is to move quickly between points of stability. Creating a stable grasp means taking into account the complex interactions between object and hand surfaces, and taking into account a variety of forces and torques. The hand must also be able to resist small external perturbations, and be able to generate restoring torques and forces to ensure manipulative stability. While all this is occurring, the hammer is lifted and transported to a location above the shelf and then placed on the shelf.

Several phases are involved in prehensile tasks that involve stable grasping. On contact with the object, the fingers are pressed against it, stabilizing the object in the grasp. If the initial point of contact is not the most appropriate, the fingers follow the contour of the object until reaching a goal location. Stabilization can potentially be broken down further into separate and distinct temporal components, as will be seen below. Once a stable grasp is achieved, it must be maintained during subsequent manipulations. These include imparting motion, such as lifting the object, moving it around, using it in task contexts, and placing the object on some support surface. Beyond these are more complex uses of objects, such as manipulating pens, musical, surgical or dental instruments, other tools and utensils. In this chapter, these phases are considered as a person creates, maintains, and then releases a stable grasp.

Making contact with an object involves a collision between two systems and, if errors are made, can have potentially disastrous effects. Creating, maintaining, and releasing a stable grasp is a complex interaction between object surfaces and the skin, and involves a variety of forces and torques. The hand is both an input and an output device. As an input device, it gathers sensory information about the state of interaction with the object during the task in order to ensure grasping and manipulative stability. As an effector, it applies task appropriate forces for grasping and manipulative stability, using the muscles (somatically innervated sensorimotor system) in parallel with the eccrine sweat glands (autonomically innervated sudomotor system[1]), given the inherent 'passive' structural characteristics of the hand (e.g., the compliant pads of the fingers and palm). The object has characteristics relevant for stable grasping which may be assessed with varying degrees of accuracy through the visual, kinesthetic, or tactile systems. As well, physical characteristics of the object's structure determine the nature of the interaction in stable grasping: for example, the object and the hand surfaces together determine the coefficient of friction.

Some object properties are found through direct interaction with the object, or haptically[2]. Grasping activates complex patterns of cutaneous, muscle and joint receptors. Gibson (1962) suggested that the covariance of cutaneous and articular motion provides information for haptic form perception. For example, Iwamura and Tanaka (1978) identified types of units in Area 2 of the parietal lobe which did not respond to ordinary passive cutaneous stimulation of the hand, nor with manipulation of wrist or finger joints by the experimenter. These neurons were selectively responsive to properties of the object being grasped. Gibson (1962) suggested that some movements are 'exploratory' and can be distinguished from 'performatory' hand movements.

Prehension is defined as the application of functionally effective forces by the hand to an object for a task, given numerous constraints. Key questions are how the hand can effect these forces and what is the nature of the forces arising in the task. This chapter addresses these questions by looking at how the hand meets the functional demands of applying forces to match the anticipated forces in the task, imparting motion to the object, and gathering sensory information about the state of the interaction with the object. First, as a key to the interface between object and hand, the skin and its properties are discussed. Then touch and active touch are addressed through a discussion of cutaneous sensors and sensorimotor integration. Force application is

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[1] Sudomotor refers to the motor innervation of sweat glands. It is derived from Latin, sudor, sudoris, meaning sweat.

[2] Haptics is a perceptual system that uses both cutaneous (including thermal) and kinesthetic inputs to derive information about objects, their properties, and their spatial layout (Loomis and Lederman, 1986).

presented through analytic robotic models, muscles as actuators, studies of pad opposition, and biomechanical studies of oppositions. Finally, the issue of imparting motion through active manipulation, using sensory information to monitor and guide motion is presented, addressing analytic models and human studies.

6.1 Skin: An Organ Critical For Grasp

"The largest sense organ of the body, interposed between the organism and its environment, skin must maintain that organism in a constant state of awareness of all environmental changes" (Montagna & Parakkal, 1974, p.157). In this sense, a constant state of awareness of all environmental changes is likely a different level of awareness from conscious awareness in the cognitive sense. Skin serves as an organ for thermoregulation, protection (including containment of body fluids and tissues) and sexual attraction; here we restrict ourselves to skin's fourth function as an organ for functional contact, manipulation and adaptation with objects in the environment (see Elden, 1971). For stably grasping, some of the relevant characteristics of skin providing sensibility, force generation and adhesion include: characteristics of epidermis, dermis and their interface; papillary ridges; eccrine glands; sensory receptors; and their innervation. We exclude lymph and blood vessels, recognizing that local changes here might affect sensibility and force generation by temperature changes, edema (swelling), or as yet undisclosed ways.

6.1.1 Skin structure and function: from fingerprints to friction

Look at your fingerprints. Papillary ridges refer to the visible ridges on the skin of the palm and fingers. The characteristic pattern of ridges and sulci on the skin of the ventral aspect of the hand, called dermatoglyphics, are found in the friction surfaces only of primates and marsupials (Montagna & Parakkal, 1974). Also called sweat or primary ridges, papillary ridges are composed of externally projecting folds of stratum corneum (the outer layer of the epidermis of skin), arranged in parallel whorls, arches or loops with distinct interunit periodicity (Montagna & Parakkal, 1974; Quilliam, 1978). These ridges, first visible in palmar and plantar surfaces of the digits of 13-week old fetuses, later extend over the entire volar (e.g., palmar) surfaces of the hands and feet; the patterns remain unchanged, and the width of the furrows increases at the same rate as the growth of the hands (Hale, 1949, 1952, cited in Montagna & Parakkal, 1974). Inked reproductions, a unique identifying characteristic or "signature", are called finger and palm prints. Most of us are familiar with medical, legal and forensic applications of fingerprints obtained through inking, otherwise called the ninhydrin reaction (Oden and von Hofsten, 1954). Yet these papillary ridges are likely more important for grasping than we have recognized previously. Interestingly, as well as human hands and feet, prehensile-tailed South American monkeys have papillary ridges on the ventral surface of the tail, and chimpanzees and gorillas have them on the weight-bearing, knuckle pads of the hands (Montagna & Parakkal, 1974). The function of such patterning is similar to the ridges on an automobile tire, to increase grip and facilitate weight bearing. The increased surface area and pattern of asperities on soles and palms provides for a better grip in walking and in grasping. The concentric arrangement of the ridges makes some asperities always perpendicular to shearing forces.

In addition to papillary ridges, Napier (1980) discussed the more pronounced flexure lines and tension lines (Langer's lines) on the hand. Permanent creases, "like skin hinges", flexure lines define the primary axes of movements about the underlying joints of the hand (refer to Appendix A). For example, the distal palmar crease is a composite of two lines. Used by palmists, the heart and head lines of humans are merged into the single simian line in nonhuman primates, reflecting the concerted motion of all four fingers perpendicular to the palm, in palm opposition. In humans, the increased independent mobility of the index finger effects a separation of the heart and head lines. Tension lines (or wrinkles, comparable to crow's feet around the eyes), reflect loss of elasticity in the skin and form horizontal lines on the back of the hand, obliquely on the thenar eminence, and vertically on the phalanges.

All skin has three layers, the surface epithelial layer, the epidermis, the connective tissue layer, the dermis, and the deepest, adipose tissue[3] layer, the hypodermis (Eckert, 1989). Quilliam (1978) and Eckert (1989) argued that the superficial fascia[4] or hypodermis, attached to the under surface of the dermis and the outer aspect of the muscles and bones, should be considered part of the skin along with the dermis and epidermis.

The epidermis or epithelial layer, about 1 mm thick in human

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[3]Adipose tissue is an aggregation of minute cells which draw fat from the blood.

[4]Fascia is the thin layer of connective tissue covering, supporting, or connecting the muscles.

digital skin, has an outer layer of anucleated, horny cells (the stratum corneum), and 4-5 inner layers of viable cells (the stratum Malpighii). Of the viable epidermal cells, the bottom, basal cells are oriented perpendicular to the surface; as they migrate upwards, epithelial cells become parallel to the skin surface. Ninety per cent of epithelial cells are keratinocytes. Keratinocyte differentiation refers to the process whereby dividing stem cells give rise to progeny cells destined to migrate upward until they die and are lost from the surface (Eckert, 1989). The migration of newly formed mitotic cells from the basal layer to the surface layer, and hence the epidermis replacing itself, takes 12-30 days in unperturbed conditions (Eckert, 1989; Montagna & Parakkal, 1974). In the transitional layer below the dead, cornified surface cells, lipid[5] filled granules fuse with the plasma membrane, and release lipid contents into the extracellular space. These form lipid-rich sheets that are believed to be extremely important in "waterproofing" the epidermis (Eckert, 1989). Other functions of this lipid sheet (e.g., as a lubricant) remain, to our knowledge, uninvestigated. Adjacent epidermal cells are attached by intercellular bridges (called desmosomes or maculae adherentes), maintaining the integrity of the epidermis (Montagna & Parakkal, 1974).

The dermis, about 3 mm thick in digital skin, is a matrix of loose connective tissue, composed of fibrous proteins, including collagen, elastin and reticulin, permeated by a semigel matrix of mucopolysaccharides. It is a tough and resilient tissue having viscoelastic properties (Montagna & Parakkal, 1974; Wilkes, Brown & Wildnauer, 1973). The elastin is insoluble, highly stable, and returns to its original shape after deformations due to stress. Microscopically, collagen has a hierarchical three dimensional organization and is composed of fibers, fibrils and microfibrils. It provides resistance to mechanical stress. Reticulin, a lipoglycoprotein, is present in very small quantities. Least understood of the dermal proteins, it may form a template for the extracellular aggregation of collagen fibrils. The dermis has deeper reticular layers composed of thick collagen fibers, and more superficial, papillary dermal layers composed of thin collagen fibers, where fingers of dermis project up into hollows of epidermis (Quilliam, 1978). It is highly vascular, containing lymph vessels, nerve fibers, nerve endings, and sweat glands.

In mammals, there are striking structural differences between

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[5]A lipid is an organic compound consisting of fats and other similar substances; they are insoluable in water.

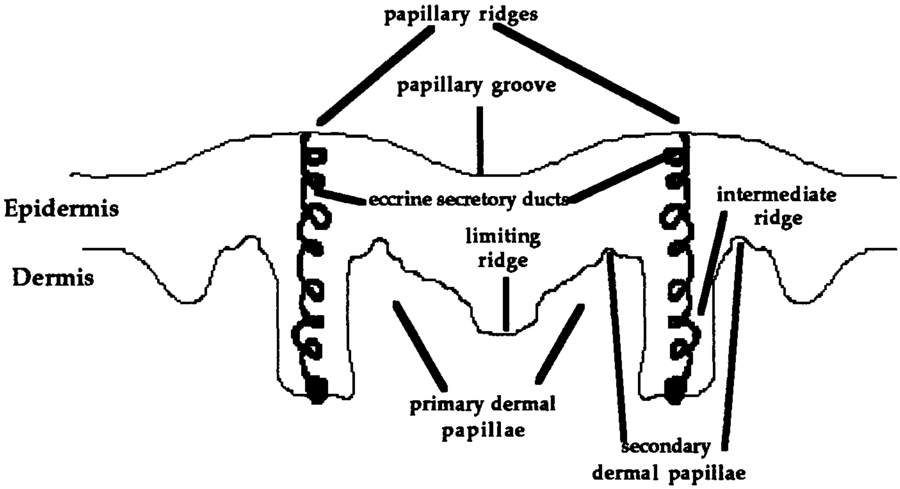

Figure 6.1 A schematic representation of the glabrous or hairless skin of the human hand. Papillary ridges, also called primary or sweat ridges, refer to the visible epidermal markings which leave fingerprints. Note that the intermediate and limiting ridges of the epidermis project down into the dermis, and that the primary and secondary dermal papillae of the dermis project up into the epidermis. The spiral ducts of the eccrine sweat glands coil their way through the intermediate ridges and surface at the center tops of the papillary ridges. The dermal papillae house Type I cutaneous mechanoreceptors: Meissner corpuscles and Merkel discs.

hairy and glabrous (nonhairy) skin (Montagna & Parakkal, 1974; Quilliam, 1978). On the hand, these can be related to the demands for grasping: the nonglabrous, dorsal skin is designed so as not to impede flexion of the wrist and fingers. The glabrous skin (palmar) is designed to comply, hold, resist pressure and shearing forces. The epidermis is always thicker and the junction of the dermis and the epidermis is much more complex in glabrous than in hairy skin. In hairy skin, the dermo-epidermal junction may be almost flat, except for cones containing hair follicles. In contrast, in the glabrous skin of the human hand, the interface between the dermis and the epidermis is highly convoluted and interdigitated. The understructure of the epidermis, unique in each part of the body, is irregular, with cones, ridges and cords of different lengths, extending different depths into the dermis. Thus the epidermis and dermis are tightly coupled; the dermis forms a negative image of the undersurface of the epidermis.

Focussing on the epidermis of the hand in Figure 6.1, we see that below a papillary ridge (also called a sweat ridge or primary ridge) on the epidermis is found an intermediate ridge on the lower surface (free floating in connective tissue). Thus, the visible ridges on the upper surface are accompanied by downwardly projecting ridges on the lower surface of the epidermis. There are also downwardly projecting ridges, called limiting ridges (firmly fixed) below the papillary grooves of the epidermis. Looking at the dermis, there are primary dermal papillae (distinct from the visible papillary ridges), interdigitating with the intermediate and limiting ridges of the epidermis. Superimposed on these primary papillae are smaller, secondary dermal papillae, often found in or near the bases of the intermediate ridges, that house Meissner corpuscles, fast adapting cutaneous receptors. A basal lamina, or basement membrane follows the contours of the basal cells of the epidermis, facing the dermis. There are anchor fibers in the membrane at regular intervals, extending into the dermis. The function of these fibers is unknown, but, along with the interdigitations, they likely serve to resist shearing forces. The glabrous skin characteristics described above are likely to bond/strengthen the interface between the epidermis and the dermis, to prevent sliding of epidermis on the dermis, to resist shearing forces and to increase tensile strength during grasping.

On friction surfaces like the finger pads, palms of the hand and soles of the feet, skin demonstrates unique characteristics important for friction, force generation, compliance[6] and other transducing and mechanical properties. These include: the cells of the horny, outer layer of the epidermis are firmly cemented together for stability; the epidermis is characterized by unique papillary ridges; there is a thick, hyalin[7] layer (stratum lucidum) of the epidermis for strength; the most complex interdigitations are seen at the dermo-epidermal junction, for resisting shearing forces (Montagna & Parakkal, 1974); the dermis is characterized by specialized mechanoreceptors for transducing skin deformation; and there are fibrous septa (a wall of fibers), passing through the subcutaneous tissue which serve to anchor the dermis to

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[6]Compliance and stiffness are analytic expressions describing the relationship between forces and displacements. They will be used informally through this chapter. Compliance, the opposite of stiffness, determines what displacements will occur in response to a force. For a more detailed view of these concepts, we refer the interested reader to (Mussa-Ivaldi, 1986; Salisbury 1985)

[7]Hyalin is a translucent protein.

the periosteum (covering connective tissue) of the terminal phalanx and to envelop fat cells in the finger pad, enabling shape adaptation to the contacting object (Quilliam, 1978). Such fat pads are present in the palmar surface of fingers, on the thenar and hypothenar eminences, and distal to the simian crease (heart/head lines) on the palm, but notably absent from the centre of the palm (Napier, 1980). When applying forces in pad opposition, the fingerpads do not displace but comply with the object's surface. When applying forces in palm opposition, the fat free centre part of the palm facilitates gripping. All these characteristics contribute to stable gripping, force generating and sensing capabilities of the hand.

Mechanical properties of the skin can be considered in terms of resting tension, nonlinear load deformation relationship, elastic, plastic and viscoelastic properties (Moore, 1972; Wilkes et al., 1973). Preexisting tension in the skin is reflected by retractiblity of skin in incised wounds, and the contraction of excised skin after removal from the body. There is nonlinear deformation; in the low load ranges, great extensions are produced by the application of small loads, but, as the load increases, the skin becomes progressively stiffer (Wilkes et al., 1973). As discussed below, as load increases, stiffness of skin increases, skin loses its ability to comply and the coefficient of friction decreases.

Elastic fibers give skin its supple characteristics while collagen provides strength, and resistance to stresses. Elastic fibers in the dermis behave like an elastomer: they have a low coefficient of elasticity. This means they can be deformed by a small force, and then recover their original dimensions even after considerable deformation. The collagen provides resistance to mechanical stress, especially compression. At rest, there is a random directional arrangement of the collagen fibers. However, when a load is applied, the collagen fibers realign parallel to the direction of force. The removal of epidermis and subcutaneous fat from excised skin has little effect on the elastic modulus or strength, indicating that strength rests in the dermis, particularly the collagen (Tregear, 1966: cited in Montagna & Parakkal, 1974). How the dermal collagen network regains its normal organization and returns to the resting state after mechanical distortion is unknown, but may be a function of the elastin fibers (Montagna & Parakkal, 1974).

Viscoelasticity is a term applied to materials such as skin that behave like neither solids nor liquids, but have characteristics typical of both. When a solid is subjected to load, stresses (forces acting to deform) are produced in the solid which increase as the load is increased. These stresses produce deformations which are defined by the strains (change from former size; Halling, 1976). Elastic solids follow Hooke's law where stress is proportional to strain, but independent of rate of strain. For skin, as a viscoelastic material, stress may be dependent on strain, rate of strain and higher derivatives of strain. As well, strain may be dependent on stress in a more complicated way. Thus the ratio of stress to strain may be time dependent or dependent on the magnitude of the stress (Moore, 1972). The implications of these factors have yet to be detailed for functional grasping.

Because of its viscoelastic properties, skin does not follow classical laws of friction, which hold for most metals (Comaish & Bottoms, 1971; Moore, 1972). First articulated by Leonardo da Vinci, Amonton's laws state that: first, friction is proportional to load,

$$F = \mu W \tag{1}$$

where F is the force due to friction, μ is coefficient of friction, and W is the normal force; and second, that the coefficient of friction is independent of the surface area of apparent contact. For a given pair of surfaces, the coefficient of friction, μ, is a constant, independent of load. Tables exist to document the coefficients of friction for different materials (see for example, Bowden and Tabor, 1967). As the normal load increases, so does the frictional force, because of an increase in the area of true contact (both in the number of contacts and in the contacting area between asperities; Bowden and Tabor, 1967; Moore, 1972). For viscoelastic materials, due to hysteresis[8] or deformation, the area of true contact is not proportional to load, W, but to the 2/3 power of load, $W^{2/3}$ (Moore, 1972). The second law does not apply to elastic and viscoelastic materials, like skin.

When compressed due to grasping, skin becomes thinner under the force, and wells up around the force, which serves to distribute the pressure. Modern views of friction recognize the viscoelastic nature of the two principal components of the friction generated between unlubricated surfaces in relative motion, adhesion and hysteresis (see Figure 6.2, for a schematic of a single ridge or asperity).

Assuming no interaction between adhesion at regions of contact and the hysteresis or deformation factor,

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[8]Hysteresis is the lagging of the effect in the body when the force acting on it is changed.

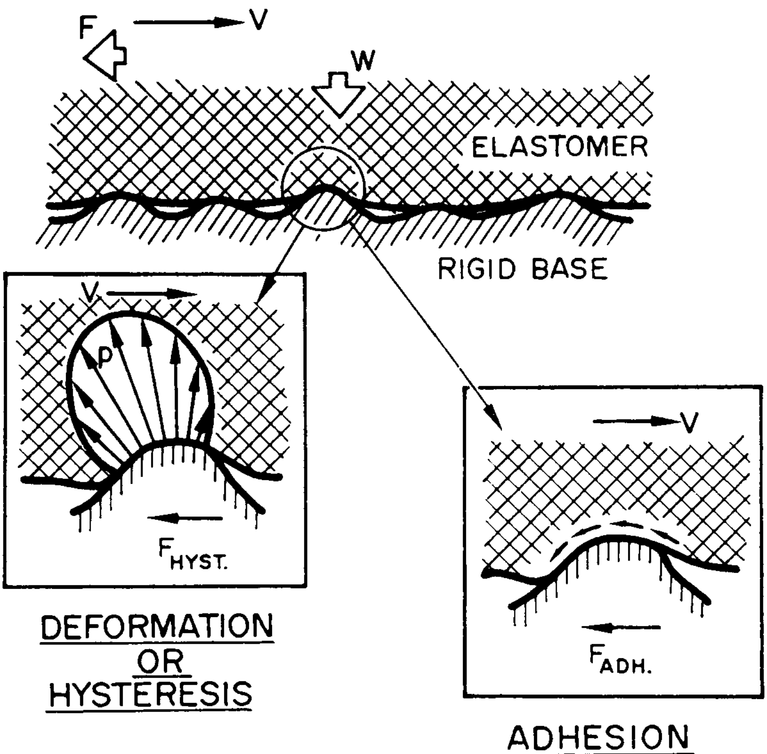

Figure 6.2 The contact area between an elastomer (like skin) and a rough support surface is characterized by the draping of the elastomer about individual asperities. The total friction force developed in sliding over a single asperity may be separated into an adhesion and a deformation term. F= total friction, $F_{HYST.}$= hysteresis friction, $F_{ADH.}$= adhesion friction, V=velocity of sliding, W=applied load, p=pressure (from Moore, 1972; adapted by permission).

$$F_{total} = F_{adhesion} + F_{hysteresis} \tag{2}$$

The adhesion component is believed to be a molecular stick-slip process (the bonding of the exposed surface atoms in both surfaces, according to a stretch, break and relaxation cycle of thermal events). The hysteresis or deformation term is due to a delayed recovery of the elastomer after indentation by a particular asperity, and gives rise to the hysteresis component. The adhesion component is a molecular surface effect whereas the hysteresis component is a bulk or macroscopic phenomenon. Both are dependent on the viscoelastic properies of the skin. Of these, adhesion is usually the larger and more important in elastomers; it can be reduced by a lubricant between the two rough surfaces in relative motion (Moore, 1972). "Indeed, if the scale of the macro-roughness is progressively diminished to a value less than the micro-roughness (perhaps approaching molecular dimensions), then it is clear that the hysteresis component of friction has been replaced at some stage by adhesional friction" (Moore, 1972, p. 234). The average molecular jump distance typical for rubber adhesion is about 100 Angstrom units, whereas the mean wavelength of the macro-roughness which determines the hysteresis component is several millimetres. With the height of papillary ridges, the volar skin of the hand lies somewhere in between, perhaps in the region of micro-roughness. Simulating use of a keyboard, some researchers have concluded that tactile friction in the finger pads is predominantly adhesive (Dinc, Ettles, Calabrese and Scarton, 1990).

Moore (1972) recommends that five distinct parameters are necessary to represent surface texture. These include factors for macro-roughness (characteristics of typical average asperities, like size, spacing and shape), as well as micro-roughness at asperity peaks and height distribution of asperities. For the visible papillary ridges of human palmar and finger skin, not all these parameters are available. Also, there are large individual differences in the characteristics of the hand skin. All of these factors need to be carefully investigated.

The result of high frictional forces is wear and abrasion. Nature is kind to replace our outer skin surfaces every 12-30 days. The generation of frictional forces between two contacting surfaces dissipates energy, giving rise to heating effects at the interface. The extent and implications of temperature rise have not been well documented for hands grasping various objects, though we consider this in the next section. A formal analysis of skin surfaces of the hand during prehension, from a tribological[9] perspective would be a valuable contribution to our understanding of human grasping. Both simulations and experiments are needed in this area.

We have considered the the structure of hand skin, and mechanical implications for grasping. Pubols (1988) suggests that many "higher order" neural and perceptual processes may be due, at least partially, to mechanical properties of the skin which provide a

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[9]Tribology is the study of friction.

focusing or sharpening mechanism, operating prior to mechanoreceptor transduction. From papillary ridges emerge the ducts of a form of exocrine glands, called eccrine glands. Thus the skin surface contacting objects is a lubricated surface, not a dry one. As well, the increased surface area due to the papillary ridges also provides room for more tactile sensory organs (Montagna & Parakkal, 1974). We now consider eccrine sweat glands, then cutaneous mechanoreceptors.

6.1.2 Eccrine glands and efferent control by the autonomic nervous system

Found on all body skin of higher primates, but only the non-hairy skin of other mammals, the eccrine glands are believed to be more important and phylogenetically more recent than the rudimentary apocrine glands. Eccrine glands develop from the epidermis (unlike apocrine glands and sebaceous glands which develop from the follicles of hairy skin, and are not discussed here), coiling downward through the dermis to subdermal fat. Half the coil is secretory epithelium and half of it is duct (see Figure 6.1). There may be 100-400/cm^2 and 2-5 million over the entire body surface (Rothman, 1954). In friction surfaces, these eccrine ducts open at the apex of papillary ridges, rarely in the furrows. Note the regularity of spacing of the pores in the center of the epidermal ridge lines of the palm in Figure 6.3.

The sweat glands of the friction surfaces of the body may be distinguished from other eccrine sweat glands on the basis of regional distribution, response to stimuli activating them, and on the basis of the composition of the aqueous sweat. Table 6.1 shows that the palms

Table 6.1 Distribution of Eccrine Glands in Humans (number of sweat glands/square inch of surface area) (from Krause, 1844, cited in Rothman, 1954; reprinted by permission)

palms	2,736	dorsa of feet	924
soles	2,685	thigh and leg, medial	576
dorsa of hands	1,490	thigh, lateral	554
forehead	1,258	cheek	548
chest and abdomen	1,136	nape of neck	417
forearm - flexor aspect - extensor aspect	 1,123 1,093		

Figure 6.3 Beads of sweat gathered at the orifices of the sweat ducts centred on the epidermal ridges of the palm (from Montagna & Parakkal, 1974; reprinted by permission)

and soles have by far the largest number of eccrine sweat glands per body surface area, compared to other body parts. Thermal sweating is characterized by a given regional response. For example, at 39-40 degrees C. and 90% humidity, responses are from (1) first, the forehead, neck, anterior and posterior aspects of the trunk, dorsa of hands and adjoining parts of forearm; (2) less from cheeks, lateral aspects of trunk and greater parts of extremities; (3) little sweating on medial aspects of thighs, less in axillae, and; (4) least on palms and soles. Notably, the palms and soles, responding late and weakly to heat stimuli respond most strongly to mental and sensory stimuli (Ikeuchi & Kuno, 1927, cited in Rothman, 1954).

The eccrine glands of humans provide visible sweating at a critical temperature and humidity, e.g., 31 - 32 degrees C. and 90% humidity. Indeed their primary identified function has been thermoregulatory. However at environmental temperatures below visible sweating, the sweat glands periodically secrete invisible sweat beads (though these are microscopically visible, as seen in Figure 6.3). This thin lubricant film of molecular proportions is referred to as boundary lubrication (in contrast to thicker lubricant films, called hydrodynamic or fluid lubrication, Naylor, 1955). The periodicity of insensible sweat gland secretion, studied most on the hand and forearm, appears to be more regular on the palmar aspects of the fingers than the dorsal aspects (Kuno, 1934, cited in Rothman, 1954). The frequency of such bursts increases with temperature, and seems to vary from 2 - 7 bursts/min. Figure 6.4 shows this periodicity in the palm of the hand. Note that relative inactivity is followed by fairly uniform discharges. Note also the marked increase in sweat discharge when the hand is gripping a dynamometer[10], compared to the palm at rest. The ability of an individual to apply forces using palm opposition appears to be correlated with this sweating.

On moderate thermal stimulation, the eccrine glands of the palms often do not respond at all. On more intense heating, palms and soles are the last regions to show sweating. In contrast, on mental and sensory stimulation, palmar and plantar sweat glands respond first and immediately. Further, palms and soles sweat most abundantly in pressure areas. Mental and sensory sweating are distinct from thermoregulatory sweating. These types of sweating include sweat production during mental efforts like arithmetic, as well as that elicited by response to visual, auditory, or cutaneous stimulation. The distinction, in terms of these regional responses of the glands and the time scale of response, suggests different parallel pathways are involved. Mental sweating occurs as fast as nerve conduction velocity permits, whereas thermoregulatory sweating has a latent period, perhaps due to the time required to raise the temperature of the skin and blood to a critical level (Kuno, 1934, cited in Rothman, 1954).

The composition of eccrine sweat and aqueous surface film is 99% water and 1% solids (Rothman, 1954). Of the solids, one half are inorganic salts, e.g., sodium choloride and one half are organic, e.g., urea. Potten (1985) indicated that the secretions were rich in lactic acid. Lobitz and Mason (1948, cited in Rothman, 1954) found a higher concentration of most salts and organic materials (e.g., chlorides, urea, uric acid and ammonia) in the intermittently produced sweat of the palm than in profusely secreted sweat. The sweat composition in the eccrine glands of the hand should be compared

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[10] A dynamometer is an instrument for measuring force or energy.

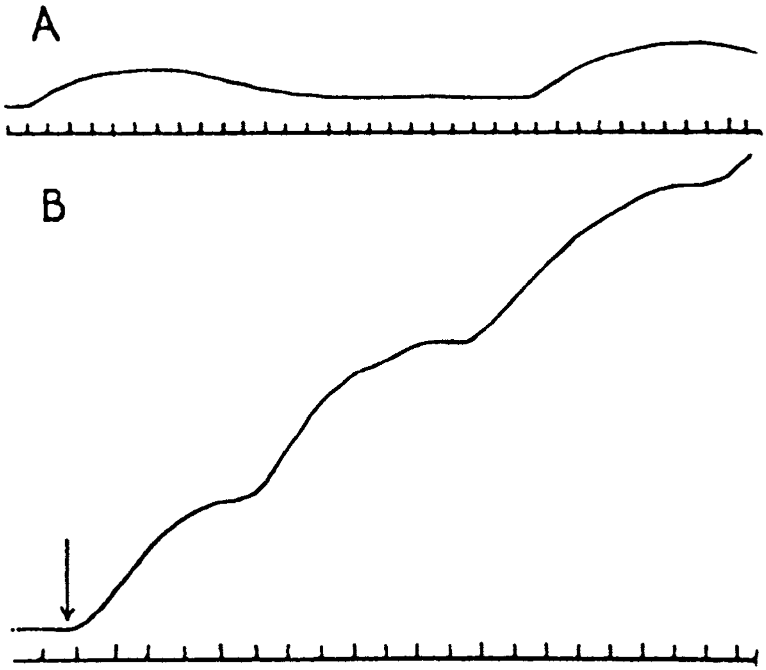

Figure 6.4 A. Discharge of sweat from a single sweat gland of the palm (secretion at rest) time marking indicates 5 seconds (Takahara) B. discharge of sweat from a single sweat gland of the palm during the grasping of a dynamometer. Time marking indicates 5 seconds (Takahara) (from Lobitz and Mason, 1948, in Rothman, 1954; reprinted by permission).

across individuals, and to other body parts, and implications of this lubrication for grasping forces studied both experimentally and computationally.

Rothman (1954, p. 164) notes, "It appears that little attention has been paid to the phenomenon which may be labeled as 'conditioning' of eccrine glands". This means that sweat glands react differently under different conditions in response to the same stimulus. For example, almost any type of thermal or mental sweating is likely to cause sweating more quickly in summer than in winter. This may be reflecting either an increase in tonus of myoepithelial cells or a heightened sensitivity due to tuning of the neural pathways, both of which would increase the responsiveness of the gland to nervous and nonnervous stimuli.

The periodicity of insensible eccrine sweating has been attributed to a central source of innervation. The secretory portion of the duct has myoepithelial cells, arranged with their long axes parallel to the tubule, and it is generally assumed that their contraction promotes delivery of sweat to the surface (Kuno, 1934, cited in Rothman, 1954). Although the pathways for this innervation are not clearly established, Guttmann and List (1928, cited in Rothman, 1954), suggest 5 main connections on the efferent pathway for generalized reflex sweating: cortex, hypothalamus, medulla, lateral horn of cord, sympathetic ganglia[11] to sweat glands. These authors indicate that "the adequate stimuli are psychic for the first neuron, thermal for the second, gustatory for the third and nonthermal skin stimuli for the fourth and fifth."

Innervation of the eccrine sweat glands is through sympathetic neurons which release acetylcholine. The sympathetic dermatomes for sweat fibers span T4-T7. The eccrine sweat glands are innervated by sympathetic cholinergic fibers, which originate from the paravertebral ganglia (Dale & Feldberg, 1934, cited in Gabella, 1976). This apparent contradiction is explained as follows. Most postganglionic fibers originating from the sympathetic ganglia are adrenergic. A minority of fibers are cholinergic, emerging from non-adrenergic sympathetic ganglion cells. Other sypathetic cholinergic fibers are vasodilator fibers to skeletal muscles and to the muscles of the tongue (Gabella, 1976). With thermal sweating, active vasodilation and sweating onset occur at about the same time. Eccrine sweat glands respond to both cholinomimetic and adrenomimetic drugs, leading some authors to argue that they have a double innervation or that the same nerves can respond to either stimulation (Montagna & Parakkal, 1972).

With respect to neural control of sweating, several points are of particular interest. One is that the cortical innervation for sweating may involve some of the same cortical areas as for grasping (see Chapters 4 and 5). Cortical lesions in the parietal area of humans often cause contralateral hyperidrosis (excessive sweating on the side of motor paresis). This has been considered due to irritation of the diseased cortical center or to the release of cortical inhibition (Linder, 1947, cited in Rothman, 1954). Cortical lesions in the premotor area (Brodmann's area 6) of cats leads to lack of sweating on the

[11] A ganglion is a mass of nerve cells serving as a center from which nerve impluses are transmitted.

contralateral side in response to 'emotional stimuli' such as a loud whistle or tapping on the nose (Schwarz, 1937, cited in Rothman). Without sweat, Moberg (1962) suggested friction on the surface of the hand would become greatly reduced. We consider below in more detail the effects of sweat on friction.

Second, denervated areas become dry, and patients often report that tools held in palm opposition, like hammers or axes are likely to fly out of their hands (Moberg, 1962). Denervated areas of palmar skin do not leave prints, and do not wrinkle when soaked in warm water (Jones, 1989; O'Riain, 1973). It would be of interest to measure these phenomena directly and relate them to grasping deficits in patients with peripheral neuropathies, more central lesions, and other injury or disease.

The final point with respect to neural control of sweating concerns the notion that nonthermal skin stimuli could be contributing to neural control of eccrine secretions. Once tactile contact with an object is made, sensory afferents could trigger increased sweating through sudomotor and sudosensory integration, though we are unaware of evidence for this. These possibilities should also be investigated.

While sweating is primarily viewed as resulting from innervation of the eccrine sweat glands, local sweating activity can occur in response to direct application of heat (in the range of skin surface temperatures of 39-43 degrees C), even in denervated areas, in anesthetized areas and areas where circulation has been arrested. Randall (1947, cited in Rothman, 1954) noted that: the latent period following heat application was usually about 1-2 minutes, there were larger droplets and increased output from individual glands, continued sweating during cooling, and, unlike nervous sweating, there was no conditioning, acclimation, or difference in critical temperature to induce nonnervous sweating in summer and winter.

How is sweating related to friction and adhesion in grasping objects? In general, friction is reduced by lubrication between two surfaces. A thin lubricant film of molecular proportions is referred to as boundary lubrication, in contrast to thicker lubricant films, called hydrodynamic or fluid lubrication (Naylor, 1955). With boundary lubrication, friction is influenced by the nature of the underlying surfaces as well as by the lubricant, whereas with fluid lubrication, frictional properties will depend entirely on characteristics of the interposed fluid layer. Invisible palmar sweat is providing boundary lubrication. Naylor (1955) showed how the coefficient of friction varies with surface conditions of the skin induced by environmental conditions. Subjects were forced to sweat by sitting under blankets, hot-water bottles and surrounded by electric heaters. After about 1/2 hour, the coefficient of friction on the forearm markedly increased, almost doubling. With air drying and cooling, the coefficient of friction fell to below resting levels; subsequent cleaning of the skin with ether brought about a sharp increase in friction, then the coefficient of friction gradually fell to resting levels. Thus friction between skin and polythene is reduced if the skin is dry, greasy or very wet, friction is increased if the skin is moist. Buchholz, Frederick and Armstrong (1988) showed also that the coefficient of friction decreased with increased levels of force in pad opposition, for all moisture and material combinations tested.

From a tribology perspective, lubricants such as sweat act differently depending on the shearing velocities between the two contacting surfaces (Moore, 1975). At low shear velocities, it has good adhesive qualities, useful in minimizing slip. At high shear velocities, the lubricant reduces friction, thus reducing wear and tear on the fingers.

Some authors (Kuno, 1934; Randall, 1947) suggested that direct sweat gland stimulation by heat hardly ever occurs for humans under natural circumstances. Others (e.g., Rothman, 1954) suggest that it is not always possible to differentiate clearly between direct/nonnervous glandular activity and that induced by nervous stimulation. For grasping, it may be that both innervation of eccrine glands and direct glandular activity due to frictional heating are critical. The motivation to grasp may innervate selectively (through the autonomic nervous system) those eccrine glands on the glabrous surfaces of the palm and fingertips. Local heating and direct glandular activity are less likely to be a sole function of thermal properties of the object-to-be-grasped, since the skin temperature leading to sweating due to radiant heating is so high that pain receptors would probably override. However, for the phases of contour following and grasping objects, it is possible that frictional forces could give rise to local heating of the skin surfaces and systematic secretion by eccrine glands to facilitate grasping goals. Alterations in lubrication may increase also the adhesive properties of the grasping surface (sticky fingers), minimizing slip. Research is needed to evaluate these hypotheses.

As summarized in Figure 6.5, there are synergistic events occurring when fingerpads make contact with an object. The eccrine glands on the palmar surface of the hand may be innervated centrally, with the commands to grasp, or peripherally, with thermal or sensory input. When the contact is made, friction is created due to the resistance of the fingers moving along the object. This creates heat

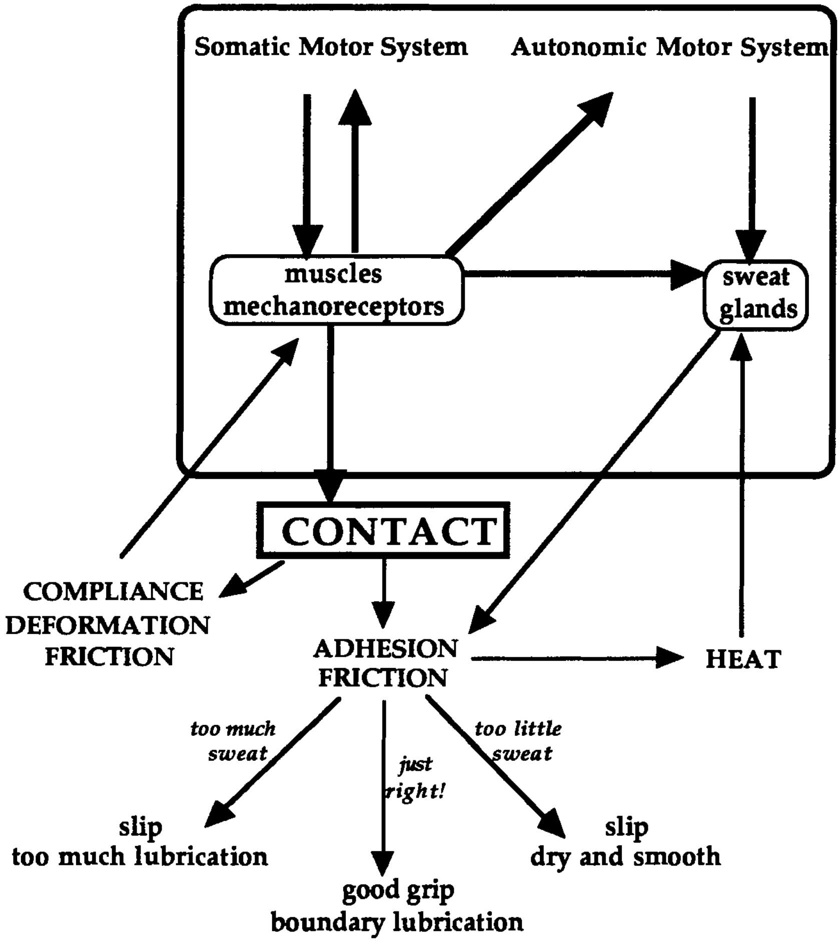

Figure 6.5. The eccrine sweat glands are innervated by the autonomic nervous system (sympathetic, but cholinergic fibers). In the cerebral cortex, lesions in the parietal or premotor areas lead to excessive sweating or lack of sweating respectively, both of which cause objects to slip from the hand. Denervation also leads to lack of sweating in those palmar areas. Healthy sweating provides boundary lubrication of the palmar surface of the hand, adhesion, and good grip. With contact, the skin is deformed, activating mechanoreceptors, and creating heat through friction. Both of these may lead to secretions by the sweat glands, though the exact mechanisms and pathways are not well defined.

which, in turn, can lead to sweat, due to the thermal properties of the system. At the same time, mechanoreceptors provide information for possible sudosensory integration, also leading to eccrine gland secretion. Either way, the mechanical properties of sweat on skin, as a boundary lubricator, are creating adhesion and preventing slip, thus enhancing the frictional component of the force without adding extra wear and tear on the fingers. Pursuing the analogy to gripping by automobile tires, a slight dampness improves the grip of both hand and tire, while wetness leads to a loss of grip in both. Napier (1980) noted that sweating is the most important feature which complements the mechanical and sensory functions of the papillary ridges.

6.1.3 Sensory receptors and afferent control by the central nervous system

Skin, muscles and joints contain receptors that transduce natural stimulus energy into electrical energy. It is of considerable historical import that in the nineteenth and twentieth centuries, physiologists, psychologists and neuroscientists who have studied these receptors have tended to focus on either skin receptors as critical for somatosensory processes and exteroception, or muscle and joint receptors as critical for motor processes, proprioception and the control of movement. Notable exceptions to this include Vallbo, Johansson, Westling, and their colleagues in Umea, Sweden, who have focussed on cutaneous mechanoreceptors with a view to their role in motor control. For grasping objects, skin receptors contribute to information about skin stretch, joint motion, contact with objects, mechanical deformations and interactions with the object in a hand centered coordinate system. Integrated with other efferent and receptor information, skin receptors can provide information about the relative location, orientation, configuration and deformation of the hand in body centered, hand centered and object centered coordinate systems.

There are about 17,000 cutaneous mechanoreceptors innervating the glabrous skin of one hand (Vallbo & Johansson, 1984). Glabrous skin contains at least four distinct mechanoreceptors, shown schematically in skin in Figure 6.6. Meissner corpuscles are located in primary or secondary dermal papillae, at limiting ridges. Ovoid in form, their long axis runs tranverse to the skin surface. Merkel's receptors or disks are also located in dermal papillae, at intermediate ridges. Pacinian corpuscles are located in subcutaneous tissue, and are comprised of onion-like rings of connective tissue surrounding the

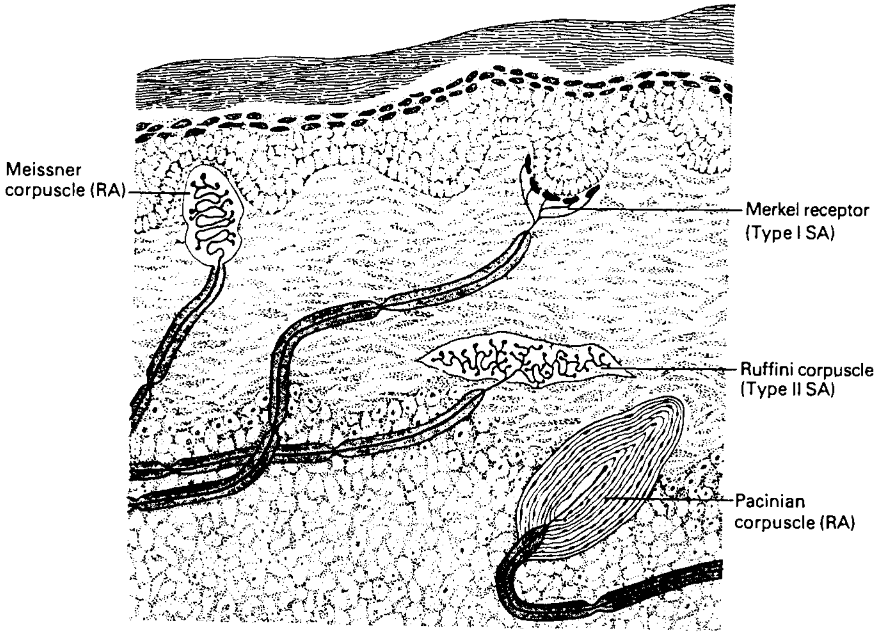

Figure 6.6 The four morphologically distinct types of mechanoreceptors in glabrous skin. Two are rapidly adapting (FA) receptors: the Meissner corpuscles, located in dermal papillae; and the Pacinian corpuscles, located in subcutaneous tissue below the dermis (in glabrous and hairy skin). There are also two slow adapting (SA) receptors: Merkel receptors, located in dermal papillae; and Ruffini corpuscles, located deeper in the demris. (from Kandel & Schwartz, 1985; reprinted by permission).

nerve terminal. Removal of these rings transforms the receptor from a fast to a slow adapting one. Ruffini ending or corpuscles are located in the deeper, reticular layers of the dermis, usually above Pacinian corpuscles.

These cutaneous mechanoreceptors give rise to myelinated, afferent fibers with similar diameters and fast conduction velocities of 35-80 m/s (Johansson and Vallbo, 1983). The mechanoreceptive afferent units have been studied extensively (Johansson, 1978; Johansson & Vallbo, 1980, 1983) and differ mainly with respect to: morphology and location of receptors; organization of afferent terminals in the spinal cord; receptive field size (the area of skin within which a stimulus excites the receptor); receptor innervation density (the number of receptive fields per unit area of skin); and adaptation characteristics (whether the receptor potential and subsequent afferent discharge decrease slowly (SA) or rapidly (FA) to a constant, maintained stimulus).

Properties of these mechanoreceptive afferent units have been extensively investigated using microneurography techniques, after Vallbo and Hagbarth (1968). Tungsten microelectrodes are inserted in peripheral (usually median) nerve fibers, and recordings are made. Electrical stimulation is delivered through the same microelectrodes to examine experienced sensations also. A summary of the results obtained by Roland Johansson and colleagues is provided in Figure 6.7. Sixty eight per cent of mechanoreceptive units arise from receptors superfically located in the dermal papillae (Type I units). The FAI and SAI units have small and well-defined cutaneous receptive fields (about 3-8 mm^2), and high innervation densities. Innervation densities are greatest distal to the whorl of the papillary ridges of the finger tips. There is also a density step at the metacarpophalangeal joint, with decreased innervation density in the palm (Johansson, 1978; Johansson & Vallbo, 1983). Their receptive fields usually span 4 - 10 papillary ridges, and Type I units are responsible for providing spatial acuity or high resolution information. Meissner corpuscles (giving rise to 43% of all mechanoreceptive afferent units) give rise to FAI fibers. Merkel's receptors or disks (giving rise to 25% of afferent units) give rise to SAI fibers. The FAII and SAII units have large, obscure borders of their receptive fields, innervate deeper receptors and are evenly distributed from the fingertips to the wrist. Pacinian corpuscles and Golgi-Mazzoni bodies give rise to FAII fibers (13% of all afferents). Ruffini endings or corpuscles give rise to SAII fibers (19% of all afferents). The two slowly adapting mechanoreceptors (SA), exhibit a static response related to the strength of the maintained skin deformation. The two rapidly adapting mechanoreceptors (FA) respond only to changes in skin deformation. These characteristics make the receptors unique for providing information about skin stretch, skin deformation (hysteresis friction), changes in deformation, and other mechanical transients relevant to the finger flexions and force applications at the interface between the grasping hand and the object.

The experienced sensations when individual mechanoreceptive units were stimulated (with a train of .2-2 microA) were of light mechanical deformations within the receptive field of the particular afferent unit. For SAI units, a light uniform pressure sensation and

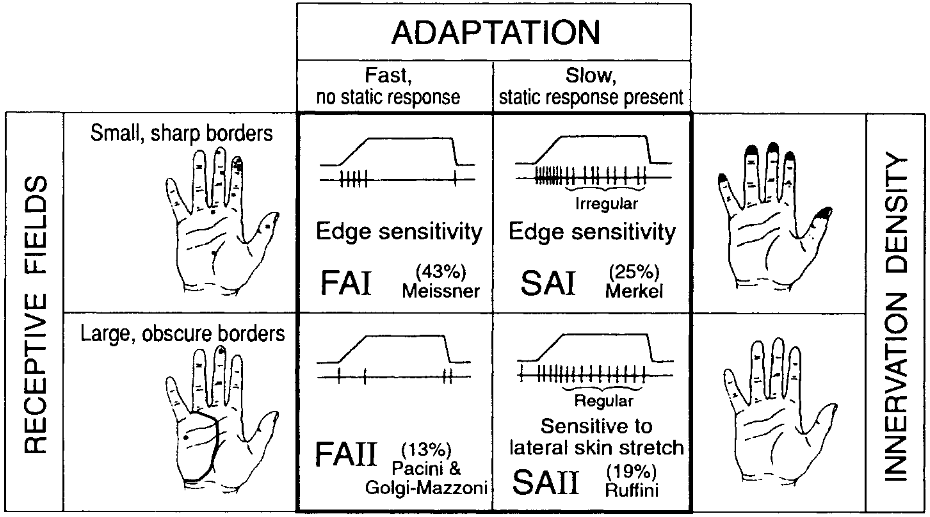

Figure 6.7. Types of mechanoreceptive afferent units in the glabrous skin of the human hand and some of their distinguishing characteristics. The graphs in the middle schematically show the impulse discharge (lower traces) to perpendicular ramp indentations of the skin (upper traces) for each unit type. The black patches and the dashed areas of the left drawings of the hand show the extent of typical receptive fields for type I and type II units, respectively. Each dot in the drawings represents a single sensory unit. In addition, the relative frequency of occurrence and the probable morphological correlate are indicated for each unit type respectively. It should be noted that the terminology of the tactile afferent units in the present account follows Johansson and Vallbo (1983) (from Johansson & Westling, 1990; adapted by permission).

for FAI unit, a buzzing, wobbling or fluttery sensation was experienced (Johansson, 1978).

In addition to mechanoreceptors in the skin and subcutaneous tissues, joint, muscle and tendon receptors are providing proprioceptive information during contact and manipulation. In examination of the deep ulnar nerve, Devanandan and colleagues, in bonnet monkeys (Macaca radiata) found that myelinated sensory fibers comprised 70% of the total nerve fibers, that 50% of myelinated fibers in nerves to the intrinsic muscles of the hand are sensory, and further that 25 - 50% of the fibers in the deep ulnar nerve innervate the joints of the hand (Devanandan, Ghosh & Simoes, 1980). Followup anatomical studies demonstrated a paucity of tendon organs in the intrinsic hand musculature, in contrast to the rich number and density of muscle spindles (Devanandan, Ghosh & John, 1983). Thus, there is a large quantum of feedback concerning movement parameters, not of evolving tension in the intrinsic muscles. They consider the role of spindles in intrinsic muscles to be, in part, providing rapid feedback in evolving manipulation so that the intrinsic muscles of the hands can be appropriately altering the resultant force vectors that act on the respective digital joints. The muscle spindle afferents in the lumbrical nerve have been implicated also in perception of direction, distinct from the perception of movement, given the loss of perception of direction with injury or administration of local anesthetic (Devanandan, personal communication, November, 1989).

It appears that there are substantial differences beween mechanoreceptors in digital joints and more proximal joints, such that digital joints are specialized particularly for detection of dynamic mechanical changes, rather than static joint position. In examining the receptors in the metacarpophalangeal joints of bonnet monkeys and one male human, Sathian and Devanandan (1983) found a dominance of dynamic mechanoreceptors: paciniform corpuscles (Type II), a smaller number of Ruffini endings (Type I) and their restriction to palmar ligaments, and a complete absence of the static receptors, Golgi endings (Type III). Free nerve endings (Type IV) and paciniform corpuscles were also found close to blood vessels, perhaps to detect mechanical changes associated with vasodilation. In the interphalangeal joints, as shown in Figure 6.8, there are some free nerve endings; however, paciniform/pacinian corpuscles are almost the exclusive encapsulated mechanoreceptors in the joints. With 3 - 50 lamellae, these were situated in groups, and exclusively in the lateral and ventral (palmar) aspects of the joint capsule (Babu & Devanandan, 1991). A single parent axon may branch and supply endings with

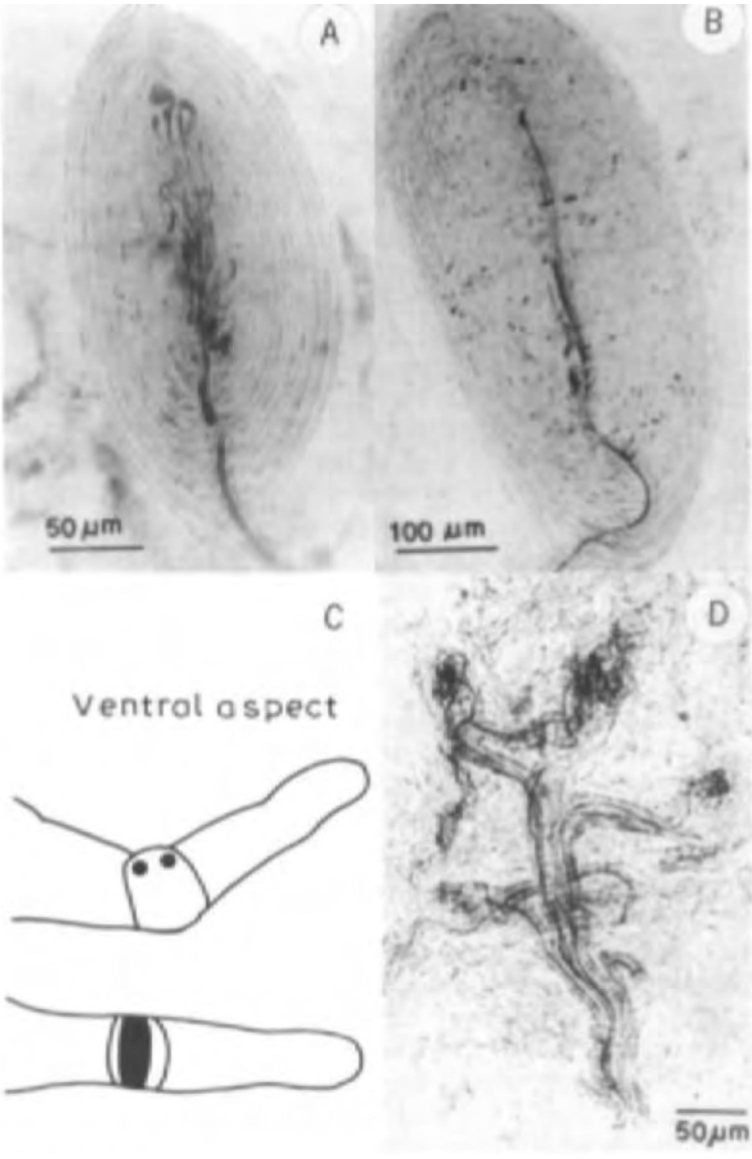

Figure 6.8 Photomicrographs of mechanoreceptors in the interphalangeal joints of the bonnet monkey. A. Paciniform corpuscle with 10 - 30 lamellae; B. Pacinian corpuscle with more than 30 lamellae; C. Schematic of the lateral and vental aspects of the proximal IP joint capsule. Darkened areas show the endings occur exclusively on the ventral and lateral aspects of the joint capsule; D. Ruffini nerve ending with one lamella (from Babu & Devanandan, 1991; adapted by permission).

different numbers of lamellae. We saw earlier that cutaneous paciniform receptors also are found subcutaneous to the glabrous, palmar skin. These fast adapting paciniform corpuscles, both in skin and joints, may be conveying information related to compliance, both in passive palmar tissue and in joint stiffness, as a function of cocontraction activity. As well, they may provide information about motion and reactive forces during object manipulation.

Proprioceptors provide information about the relative position of body segments to one another and about the position of the body in space, including information about mechanical displacements of muscles and joints. Integrated with other efferent and receptor information, joint and muscle receptors are critically important during both the free motion phase discussed in Chapter 5 and the compliant motion, force generating phase, of interest here in Chapter 6. When the hand is in contact with objects, proprioceptors contribute to information about both object and body: skin stretch, joint motion, mechanical deformations, compliance, geometry of contact, and interactions with the object in a hand-centered coordinate system. It is possible that the functional roles of joint, muscle and skin receptors are fundamentally different during free motion and compliant motion phases. Thus, there may be differences in the information communicated by their afferent activity during the two phases, in the patterns of integration of these sensory signals at segmental levels and with descending motor commands, hence in the patterns of motor unit recruitment, and control of muscles by the CNS.

6.2 Active Touch and Sensorimotor Integration

Phillips (1986, p. 1) refers to the the glabrous skin of the fingertips as the somesthetic macula[12], noting that "our explorations of tactual and visual space require active movements of the 'sensifacient fields' to centre their respective maculae on objects of interest". Comparisons and contrasts between the eye and the hand were earlier traced to Charles Bell (1833), who discussed what is currently known as 'foveation' in which there is active control of the eye to place an object on the fovea/macula of the retina. Such comparisons and contrasts should be expanded further, including the roles of reflexes, postural support, automatic and voluntary control, efference copy or outflow, somatic and autonomic innervation, accommodation and

[12]The macula lutea of the eye contains the fovea which is the area of greatest visual acuity.

assimilation, and control systems analysis. Our point here is that like the eye, the sensory and motor functions of the hand are intertwined and indivisible, as the hand is moving to grasp, feeling to grasp, grasping to feel and grasping to move objects. This ability, called active touch or haptics, is highly developed in the human sensorimotor system.

Active touch, or touching was distinguished from passive touch, or being touched by Gibson (1962), who noted that with active touch, the impression on the skin is brought about by the perceiver. Active touch, our concern here, is an active exploratory sense. Through exploratory movements, tactile scanning can occur, providing information about object properties.

6.2.1 Wielding a stick: feeling object length

In an extensive analysis of perception of length, weight, and centre of mass in lifted rods, Hoisington (1920) showed that for non-visual perception of length of a rod lifted or held in palm opposition, the underlying essential condition is a ratio between two opposing pressures, held together by directional and temporal relations; in addition to the two opposed pressures are the absolute intensity of the impressions, their temporal course, the pressure gradient formed and the muscle and strain sensations from the hand and arm. Center of mass of the object bears a constant direct relation to the ratio of opposing pressures, but is removed from the experienced perception.

Perceptions of length reachable by hand-held rods, partial and total rod lengths have been evaluated by Burton, Solomon, and Turvey who suggested that the moments of inertia provided the kinetic bases for judgements of rod length (Solomon & Turvey, 1988; Solomon, Turvey & Burton, 1989; Burton & Turvey, 1991). To hold stationary a rod held in the hand, the forces and torques that must be applied are a function of the type of opposition (in this case, palm opposition), virtual finger mapping, hand configuration, hand placement on the rod, and the physical dimensions of the object. Placing added weights and the hand at different positions along the length of the rod altered perceived length in predictable ways according to the center of mass, and moment arm length, consistent with the earlier statements of Hoisington (1920) on ratios of opposing pressures and intensities in the hand and arm. Burton and Turvey (1991) address the questions of corresponding deformation patterns in the hand and how prior intents are functionally equivalent to physical constraints that harness dynamics to form task-specific mechanisms (see Chapter 8 on Constraints).

6.2.2 Holding and jiggling: discriminating weight

To appreciate and discriminate the weight of an object, some have held the view that humans depend on centrally generated commands (efference copy or sense of effort) more than peripheral afferent information (e.g., Gandevia & McCloskey, 1977a,b,c). Others have suggested that the sensory afferents from muscles and tendons are critical (e.g., Roland & Ladegaard-Pedersen, 1977). Victor Raj, Ingty and Devanandan (1985) examined healthy individuals and leprous patients with chronic anesthesia of the hands, in their ability to discriminate weights with passive skin compression, compared to active flexion about the elbow or metacarpophalangeal joint. They found that active movements of the digits were required for forces smaller than 100 g to be appreciated. Although afferent information was sufficient to discriminate weights greater than 100 g, active movements of the digits signicantly increased the sensitivity of the discrimination. Elbow movements were much like cutaneous stimulation alone. Based on the assessment of leprous hands, and comparisons with healthy hands, they suggest that in humans the afferents from the extrinsic hand muscles cannot adequately sense the smaller forces (less than 100 g), and such force appreciation must be dependent on the intrinsic hand muscles, and digital joints as well as cutaneous afferents.

Compared to holding, 'jiggling' an object has been shown to improve performance on a forced-choice weight discrimination task (Brodie & Ross, 1985). Grasping with pad opposition, they had subjects lift cylinders to a marked height of 20 cm (described as using the shoulder as a fulcrum for the lift), then holding or "jiggling", then lowering the object. Jiggling consisted of repeated vertical movements for 3 sec. They used cylinders (4.5 x 2.5 cm) weighing 52 to 64 g, in 2 g. intervals. They considered a number of options explaining the advantage of jiggling over holding, including that jiggling provides inertial cues to mass beyond the forces required to overcome gravity, and that receptors may be functioning optimally, through a complex interaction betwen efferent and afferent signals.

For the complexity of weight appreciation, Marsden, Rothwell, and Traub (1979) emphasized the need to seek more experimental evidence in order to evaluate the importance of different sources of information.

6.2.3 Object properties: Exploratory procedures

Lederman and Klatzky (1987) developed a set of *exploratory procedures* that summarize the exploratory uses of hands to extract salient object features (Figure 6.9). An exploratory procedure (EP) is a highly stereotypic motion pattern for obtaining information about some characteristic of an object. <u>Lateral motion</u> between the skin and object is used to extract texture. The typical features of this motion are rapidity, repetition, and positioning on a homogeneous portion of the object surface rather than along an edge. <u>Pressure</u>, involving a normal force or torque on one part of the object, is used for determining hardness. <u>Static contact</u>, where the object is supported externally and the hand rests on the object without molding to it, is used for thermal sensing. <u>Unsupported holding</u>, or hefting, where the object is lifted and maintained in the hand and molded to the object, is used for weight. <u>Enclosing</u> around the object (i.e., static molding of the hand) provides knowledge about volume and global shape i.e., the coarse envelope of the object. <u>Contour following</u>, where the hand makes smooth nonrepetitive movements within a segment of the object's contour, is used to learn exact shape, ie., the fine, spatial details.

Through a battery of experiments (Klatzky, Lederman, & Reed, 1987; Klatzky & Lederman, 1990), Klatzky and Lederman identified properties of objects to which either the visual system or the haptic system have access. These include surface properties (texture, hardness, and temperature) and structural properties (global shape, exact shape, volume, and weight). Various properties affect the method in which the hand can apply the forces. For example, shape and size constraints affect how many fingers can be used and where they can be placed; shape interacts with weight to constrain where the fingers must be placed; and hardness interacts with weight to constrain how many fingers can be used. Hardness also affects how forces can be applied to the object in order to impart motion, and texture affects the application of forces, due to frictional considerations. Lederman and Klatzky argued that humans use EPs to gather sensory information. They have noted invariant and typical features with which subjects get the sensory information needed for a specific task. For example, to gain texture information, lateral motion between the skin and object is used. The typical features of this motion are rapidity, repetition, and positioning on a homogeneous portion of the object surface rather than along an edge. Any kind of movement will encode texture; therefore, the EPs of enclosing and contour following will also provide textural information (see Table 6.2). To test weight,

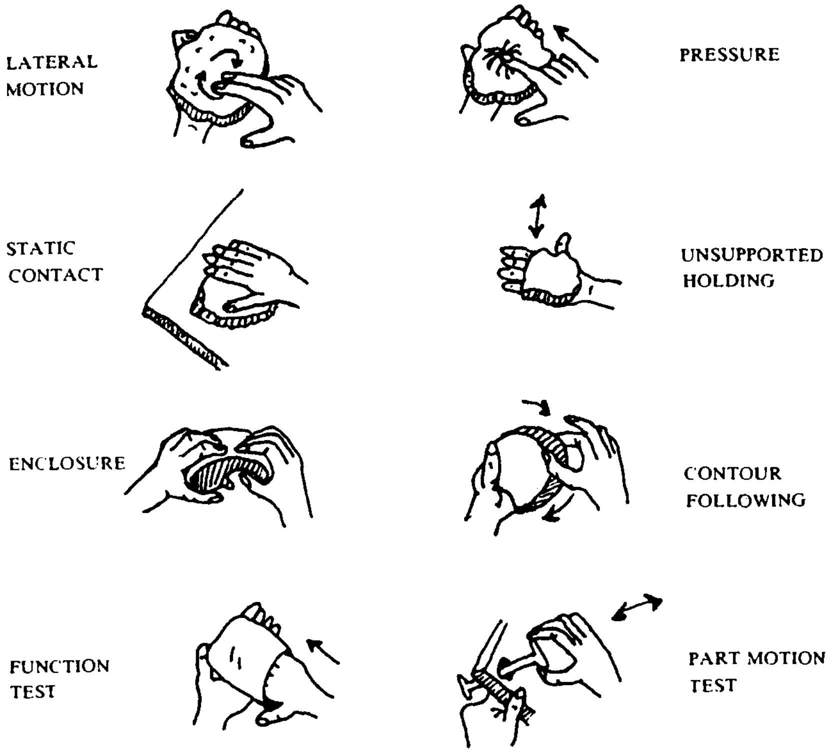

Figure 6.9 A set of exploratory procedures (EPs) that subjects use when trying to gain information about an object using haptics or active touch (from Lederman & Klatzky, 1987; reprinted by permission).

unsupported holding is used, as an object is lifted and maintained, it is molded by the hand. Enclosure of the fingers around the object generally provides texture, hardness, and shape information. In pad opposition, contact and pressure by the finger and thumb distal pulps during lifting (unsupported holding) provide accurate information about weight and hardness for small objects. Because less skin is contacting the object in pad opposition versus palm opposition, less reliable information about temperature is provided. And unless the fingers are initially misplaced and must be repositioned by following the contour of the object, determination of texture may be only poorly noted. However, Johansson and Westling (1987) have shown that as

Table 6.2 The relationship between sensory modality and object properties. While one EP seems to be stronger in extracting information, others secondarily encode the information. EP=exploratory procedure. From Lederman and Klatzky (1987) and Klatzky and Lederman (1987).

Object Property	Primary EP	Modality	Secondary EPs
Texture	lateral motion	spatial density: vision roughness: haptics	contour following enclosing static contact
Hardness	pressure	haptics	enclosure lateral motion contour following
Temperature	static contact	haptics	enclosure contour following
Weight	unsupported holding	haptics	enclosure contour following
Volume (or size)	enclosing	vision	static contact unsupported holding contour following
Exact Shape	contour following	vision	
Global shape	static contact	vision	contour following unsupported holding enclosure

human subjects lift objects in a two fingered pad opposition, microslips (small movements of the object against the skin) occur that are below the level of conscious awareness. The fingers continue to apply pressure until these microslips disappear, suggesting that the CNS adjusts to the ongoing frictional conditions (due to state of the distal pulps, surface texture, contact area and object weight) as long as the muscles are set for some range of values.

The relationships between object properties and how subjects get the sensory information needed for a specific task (Table 6.2) have been identified (Klatzky & Lederman 1987; Klatzy, Lederman, & Reed 1987). Texture is better found haptically than visually, although both encode them well, because texture has two components (spatial density which is more accessible to vision, and roughness which is more accessible to touch). Any kind of movement will encode texture; therefore, the EPs enclosing and contour following will also provide texture information. Statistically, static contact between the palmar surface of the hand and object will work as well. Hardness is a feature better found haptically. In order to apply pressure, the object must be stabilized either by the environment, the other hand, or by other fingers. Pressure can be applied while performing lateral motion, contour following, or enclosure. Subjects appear to encode hardness along with texture. Hardness is measued by pressure, which is quickly assessed and easily executed on a homogeneous object. It also seems to be the most specialized procedure. Temperature is a feature better found haptically, and can be determined statistically as well by enclosure and by contour following. Weight tends to covary with size (large objects tend to be heavier). Weight is a feature better found haptically than visually. These researchers suggest statistically all EPs will extract weight.

In terms of visually-determined features, volume is a feature better found visually. Enclosure is quick but only conveys gross size information. However, it seems to be the least specialized. Contour following may occur for larger objects. As well, statistically static contact and unsupported holding will convey volume. Shape is a feature better found by the visual system, which is good at spatial analysis of patterns. Contour following does not occur on a homogenous surface; it is a relatively slow procedure and subject to error (due to memory and integration). Enclosure is quick but only conveys low level information. Global shape can be determined by static contact, contour following, and unsupported holding.

6.3 Analytic Model of Grasping

An object has a weight, acting at its center of mass (see Figure 6.10). The forces applied by the virtual fingers to the object's surfaces must counterbalance this weight sufficiently in order to overcome gravity and lift the object. These applied forces, supplied by the muscles or tendons acting on the joints, are transmitted through the fingerpads (in pad opposition) against the object's surfaces. Identifying human hand postures and muscle commands that will solve this problem is similar to problems in the field of robotics, where researchers develop algorithms to determine whether a particular robotic grip imposes sufficient constraint on a grasped object. Aspects of this analysis involve how the forces are transmitted through the fingertips, how the fingertip forces relate to joint torques,

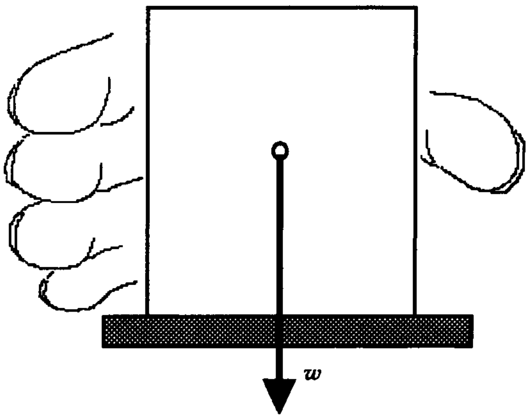

Figure 6.10 Hand about to grasp object. Two virtual fingers each apply a force in opposition to each other in order to hold the object. In order to lift the object, they must counteract the weight of the object. The object rests on a table, supporting the weight of the object.

and the conditions for a stable grasp. In this section, these topics are explained.

6.3.1 Force transmittal in robotics

When two surfaces come into contact, they may move in order to maintain or break the contact. If there is sufficient friction between the two contact areas, then motion in directions resisted by the friction forces will not be possible. Formally, a contact is a collection of adjacent points where touching occurs over a contiguous area (Salisbury, 1985). A contact point is characterized by having a position (coordinates of the point), orientation (direction of the surface normal), and curvature (maximum and minimum radii of curvature). A contact normal is an outward-pointing surface normal tangent to the plane at the point of contact. Salisbury (1985) noted that different types of contacts are possible. <u>Point contacts</u> occur when the radii of curvature are very small, such as when two real fingers are used to grasp a basketball. Assuming that contact is maintained and assuming there is friction between the fingerpad and basketball, then each contact can be modelled as three different twists to <u>specify the relative motion</u> of that fingerpad against the basketball. A <u>twist</u> is a six vector

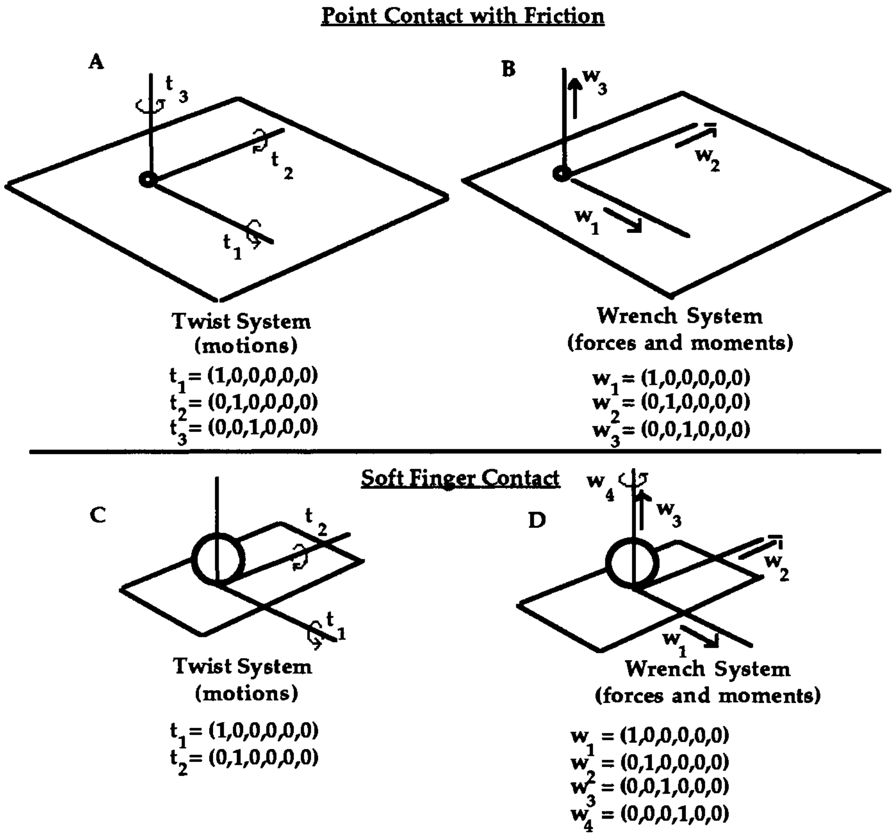

Figure 6.11 Two examples of contacts between two objects. A. A point contact with friction allows relative rotational motions about three twist axes B. A point contact with friction can resist forces along three wrench axes C. A soft finger contact allows relative rotational motions about two twist axes D. A soft finger contact can resist forces along three wrench axes and it can resist a moment about one wrench axis. A wrench system and a twist system at a contact are reciprocal, or orthogonal, to each other (from Salisbury, 1985; adapted by permission).

$t=(T_1,T_2,T_3,T_4,T_5,T_6)$, where T_1, T_2, and T_3 are infinitesimal rotational motions about a twist axis and T_4, T_5, and T_6 are infinitesimal translations along a twist axis. A point contact with friction is shown in Figure 6.11a, where contacting a plane is used for simplicity. The twists are two rotations around the radii of curvature of the fingerpad and one twisting motion of the finger (as if spinning the basketball on the fingertip). These three twists define a twist system at the point of contact. Another type of contact that more closely models a human finger pad[13] is the soft finger in contact with a standard sized object such as a golf ball. A soft finger is similar to the point contact with friction, but as seen in Figure 6.11c, this twist system has only two twists (the two rotations around the radii of curvature). This is because the fingerpad has a contact area large enough to resist moments about the contact normal (no relative spinning motion).

A set of forces and moments acting on an object acts as a single force along a wrench axis and a moment exerted about the axis (Salisbury, 1985). A wrench $w = (f_x, f_y, f_z, m_x, m_y, m_z)$ specifies the forces and moments that can be resisted by the contact, where f_x, f_y, f_z are the components of net force, and m_x, m_y, m_z are the components of net moment. A wrench system is the collection of wrenches at the point of contact. With the basketball example (Figure 6.11b), the finger can resist forces along three axes: it can resist the force of the basketball pushing against it along the contact normal, and it can resist forces along the basketball surface tangential to the contact normal. Since wrenches and twists are reciprocal to each other, four wrenches are possible in the golf ball example (Figure 6.11d). These are the three wrenches from the basketball example and in addition, the finger can resist the moment about the contact normal.

Salisbury (1985) gives an example of two soft fingers in contact with an object, as seen in Figure 6.12. Following Figure 6.11, each finger has four wrenches resisting the external forces acting on the object. The weight, acting at the object's center of mass, is the external force on the object. Wrench w_1 acts in a positive x direction. Wrench w_1 and w_2 are normal to the surface and are maintained positive in order to assure contact with the object and to allow friction to be active. Therefore, wrench $w_1=[1,0,0,0,0,0]^T$ and $w_2=[-1,0,0,0,0,0]^T$ (w_i are column vectors; the transpose of a column vector, indicated by the T, is a row vector). Wrench w_3 acts in a positive y direction but also can resist a moment around z; the same is true for w_5. Wrenches w_4 and w_6 act in a positive z direction but also

[13]See Cutkosky and Wright (1986a) for a contact model that even more closely resembles the human fingertip. It is a soft, curved finger which is a compliant fingertip that conforms to the object surface and adheres slightly, while also exhibiting the ability to roll, shifting the location of the contact point.

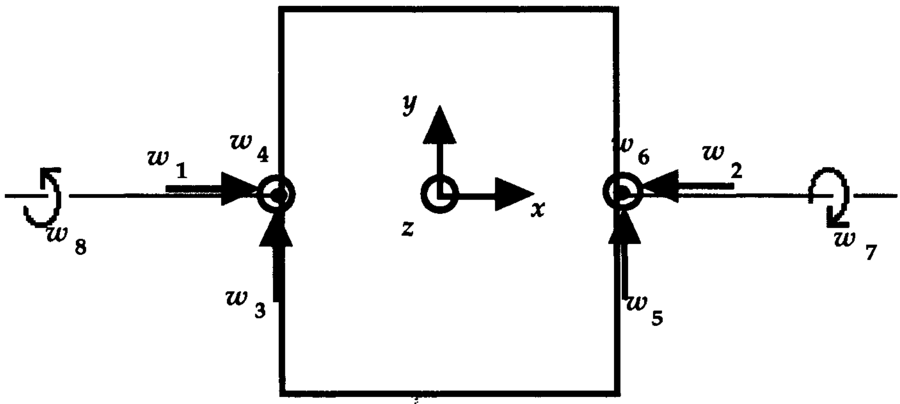

Figure 6.12 Two soft fingers in contact with object. The wrench system from finger 1 has four wrenches (w1,w3,w4,w8) consisting of three forces and one moment relative to the contact normal. The wrench system for finger 2 (w2,w5,w6,w7) is similar. Wrench w_1 and w_2 are normal to the surface and are maintained positive in order to assure contact with the object and to allow friction to be active. The object has a coordinate frame centered at its center of mass (from Salisbury, 1985; adapted by permission).

can resist moments around y. Finally, wrenches w_7 and w_8 can resist moments around x. A wrench matrix $\boldsymbol{W}$ can be formed such that $\boldsymbol{W} = [w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8]$, or

$$\boldsymbol{W} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \qquad (3)$$

When two wrench systems act on an object, some wrenches may intersect, and the effect of a wrench in one system can be counterbalanced by a wrench in the other system. These intersecting wrenches are called internal forces. For example, w_1 from the left contact and w_2 from the right contact in Figure 6.12 are internal forces, and so are w_7 and w_8. But ***W*** is just a collection of unit vectors (with magnitude of 1). The magnitude of a wrench is defined as an intensity. Increasing the intensities of w_1 and w_2 will not impart motion to the object, only hold it tighter. Algebraically, this pair of equal and opposite wrenches correspond to a homogeneous solution to the problem of finding contact wrench intensities that satisfy

$$\boldsymbol{WF} = w \tag{4}$$

where ***F*** is defined to be an n-vector of contact wrench intensities for the n contact wrenches and w is the external force (from Figure 6.10, the external force is the weight of the object). In terms of grasping, a solution to Equation 4 describes the forces and moments (with magnitudes ***F*** and directions ***W***, as transmitted through the modelled contacts) that are necessary to counteract the weight of the object. Included in the solution are any internal forces that are applying forces without imparting motions.

Researchers in robotics have proposed various methods for finding a solution for Equation 4. Salisbury (1985) defined the grip transform G, which is built from ***W*** by turning it into a square matrix by adding to it the magnitudes of the internal forces. Yoshikawa and Nagai (1990) define the internal forces between three contact points as the unit vectors directed between them, and develop grasp modes for grasping arbitrarily shaped objects. Li and Sastry (1990) use an optimization technique so that they determine a configuration based on a grasp quality measure.

In terms of the model of opposition space presented in Chapter 2, virtual fingers are applying forces against the object along the contact normals. The Force Orientation constraint identifies the internal forces of the virtual fingers, while the magnitudes are constrained by the Force Magntitude constraint. These internal forces are applied along the opposition vector of the object, using ***WF***=w. A homogeneous solution to ***WF***=w in effect identifies an opposition vector between the two wrench systems with a magnitude equal to the width of the object. In pad opposition, the pads of the fingers must be in opposition in order to supply internal forces along the opposition vector; for palm opposition, the finger surfaces oppose the palm; and in side opposition, the pad of the thumb opposes the radial hand surfaces.

6.3.2 Fingertip force and joint torques

We have just considered the issue of transmitting forces through the fingertips in order to counterbalance the weight of the object. The vector $\boldsymbol{F}$ identifies the required intensities of the wrenches at the fingertips. The second issue to consider is how those forces are generated in an intrinsic body space, such as muscle lengths. In robotics, a similar but somewhat simpler problem is to determine the forces and torques at the joints that will generate these desired fingertip contact forces. Multi-jointed fingers in a hand apply forces at the fingertips that are a function of the joint angles and the forces and moments at the joints. What is needed is a relationship between the contact forces and the joint torques.

Starting with one finger with three joints, a coordinate frame is placed at the fingertip, as seen in Figure 6.13. The infinitesimal joint angles of the jth finger, $\delta\phi_j=[\delta\phi_{j1},\delta\phi_{j2},\delta\phi_{j3}]^T$ can be transformed to a fingertip position (x,y,z) and orientation (ϕ_x, ϕ_y, ϕ_z) as follows:

$$\begin{bmatrix} x \\ y \\ z \\ \phi_x \\ \phi_y \\ \phi_z \end{bmatrix} = J \begin{bmatrix} \phi_{j1} \\ \phi_{j2} \\ \phi_{j3} \end{bmatrix} \tag{5}$$

where J is the Jacobian matrix that maps from joint space (the joint angles) to Cartesian space (end point position and orientation). Let t_j be the twist system at the jth finger. Then, for the jth finger, Equation 5 can be written as:

$$t_j = J_j \phi_j \tag{6}$$

For a five fingered hand, equation (6) expands into the following:

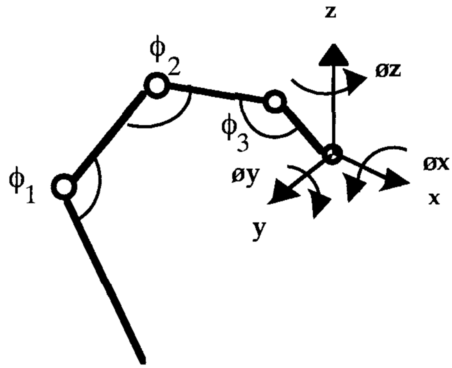

Figure 6.13 One multi-joint finger. The position and orientation of the fingertip in a Cartesian coordinate frame placed on the tip of the finger is a function of the joint angles.

$$\begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \end{bmatrix} = \begin{bmatrix} J_1 \vdots 0 \vdots 0 \\ 0 \vdots J_2 \vdots 0 \\ 0 \vdots 0 \vdots J_3 \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{bmatrix} \tag{7}$$

or

$$\lambda = \boldsymbol{J}\phi \tag{8}$$

where $\boldsymbol{J}$ is the composite Jacobian matrix composed of the individual finger Jacobians; λ is the set of twist systems at the five fingertips; and ϕ is the joint angles for the fingers. In order to determine joint angles from the end point position and orientation, the inverse of $\boldsymbol{J}$ would be needed. Recalling $\boldsymbol{F}$ as the set of wrenches $[w_1,w_2...w_n]^T$ at the contacts and defining τ as the torques $[t_{j1},t_{j2},t_{j3}]^T$ at the joints, then

$$\boldsymbol{F}^T\lambda = \tau^T\phi \tag{9}$$

Equation 9 relates the force at the fingertip (left-hand side of the equation) to the torques at the joints (right-hand side). In effect, it is a statement about the work[14], or virtual work, of the system. The virtual work on the left-hand side of the equation describes the work put into the system, and the virtual work on the right side of the equation describes the work done by the system.

Combining Equations 8 and 9, we get:

$$F^T \boldsymbol{J} \phi = \tau^T \phi \tag{10}$$

Simplifying,

$$F^T \boldsymbol{J} = \tau^T \tag{11}$$

or

$$\tau = \boldsymbol{J}^T F \tag{12}$$

where $\boldsymbol{J}^T$ is the transpose of $\boldsymbol{J}$. The Jacobian $\boldsymbol{J}$ can be used to determine what torques and forces τ must be applied at the joints to cause it to exert a net generalized force (or wrench) $\boldsymbol{F}$ at the end point.

The goal in opposition space planning is to find an opposition space for the given opposition vector. The opposition vector is a homogeneous solution to $\boldsymbol{WF}$=w where w is the weight of the object and the magnitude of the opposition vector is equal to the width of the object. For pad opposition, the orientation of the finger pads is a function of the real finger joint angles (proximal and distal interphalangeal joints and metacarpophalangeal joint), and not the virtual finger state variables angle ϕ_i and length λ_i. Therefore, the Jacobian $\boldsymbol{J}$ is a non-linear mapping between the virtual finger forces applied at the grasping surface patch and the virtual finger state variables.

6.3.3 Stable grasp

In Chapter 2, many human hand prehensile functions were discussed, and in this chapter, the use of those functional features has been noted. Yet, underlying many prehensile tasks, a fundamental task constraint remains to 'not drop the object.' In a formal sense, what does it mean to grasp and not drop an object? Two aspects of

[14]Work is defined as a force acting over a distance.

this will be considered here. The first has to do with the object slipping from the grasp; the second has to do with counteracting perturbations to the posture.

In terms of resistance to slipping, a stable grasp has three necessary conditions (Fearing 1986):

1) The object must be in equilibrium (no net forces and torques). That is to say,

$$\sum_i \vec{F}_i = 0 \tag{13}$$

$$\sum_i \vec{r}_i \times \vec{F}_i = 0 \tag{14}$$

where F_i are the force vectors acting on the object and r_i are the distance vectors from a point on the object to the location of force application.
2) The direction of the applied forces must be within the cone of friction, so that there is no slip at the fingers. As seen in Figure 6.14, a force applied to a surface generates a normal component, F_n (due to surface stiffness), and a tangential component, F_t (due to friction). As was mentioned in Section 6.1.1, the relationship between these depends on surface properties of both the finger and the object, and it is called the coefficient of friction, μ, or

$$\mu F_n > |F_t| \tag{15}$$

The arc-tangent of the coefficient of friction defines an angle, ϕ, where

$$\phi = \tan^{-1} \mu \tag{16}$$

The set of all vectors within twice this angle forms the cone of friction. The applied force makes an angle α with respect to a surface normal and as long as this angle is within this cone of friction, there will be no slip of the fingertip along the edge of the object.
3) It should be possible to increase the magnitude of the grasping force to prevent any displacement due to an arbitrary applied force. When the applied force is larger than the friction forces, it is

necessary to increase the normal force at each finger to prevent object displacement.

To restrain a rigid planar body from motion under conditions with friction, two fingers are necessary. The fingertip forces F_1 and F_2

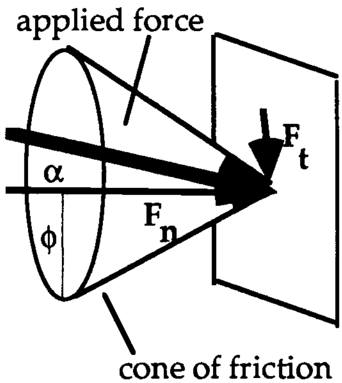

Figure 6.14 An applied force, F, has two components, a tangential force, F_t, and a normal force, F_n. It makes an angle α with a vector normal to the surface. The cone of friction is a geometric interpretation of the relationship between the two contacting surfaces.

applied by these two fingers to an object can be seen in Figure 6.15. Each finger makes an angle α_i with a normal to the surface, measured in a counterclockwise sense. To prevent sliding, these angles must be within the cone of friction, satisfying

$$\phi > \alpha_1 > -\phi \tag{17}$$

$$\phi > \alpha_2 > -\phi \tag{18}$$

For equilibrium, F_1 and F_2 must be colinear, of equal magnitude, and opposite in sign to satisfy the first condition of a stable grasp. If they are not colinear, rolling will occur. The two force angles are not independent, and are related by

$$\alpha_2 = \alpha_1 + \psi \tag{19}$$

where ψ is the angle between the surface normals measured from the

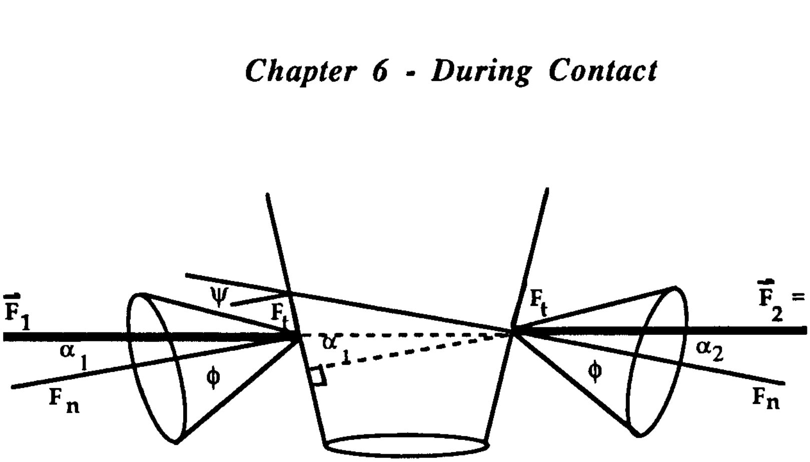

Figure 6.15 Two fingers applying point contact with friction against an object. Each finger makes an angle α_i with a normal to the surface. For equilibrium, F_1 and F_2 must be colinear, of equal magnitude, and opposite in sign.

normal at F_2 to the normal of F_1. Substituting, we get

$$|\psi| < 2|\phi| \tag{20}$$

Fearing (1986) mentions that the closer the sides are to parallel, the smaller the coefficient of friction required to grasp them stably.

The second aspect of a stable grasp is counteracting perturbations; i.e., determining whether the grasp posture will return to its initial configuration after being disturbed by an external force or moment. This could occur, for example, when a grasped hammer comes into contact with a nail. Will the hammer stay in the grasp, or will it go flying out of the hand? While modelling a three dimensional stable grasp with soft fingers has been done (Nguyen, 1987a, b), a much simpler model will be presented here for clarity.

Nguyen (1986b) models two-dimensional grasps using point contacts without friction. A grasp consists of a set of fingers making contact with the object (planar in this case). A finger F_i is modelled as a virtual spring[15] with linear stiffness k_i. Ths stiffness can come from the stiffness of the tendons, the viscoelastic properties of the fingers, or even from using active stiffness to control the fingers. The finger compresses when the object is moved away by (x,y,θ) from its equilibrium. Assuming that the object's weight is perpendicular to the

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[15]The potential energy of a spring is $U = \frac{1}{2}kx^2$.

grasping plane, the potential function of the grasp is equal to the sum of the potentials of all its springs:

$$U(x,y,\theta)=\sum_{i=1}^{n}\frac{1}{2}k_i\sigma_i^2(x,y,\theta) \tag{21}$$

where k_i is the spring constant, σ_i (x,y,θ) is the compression at finger F_i, and n is the number of fingers in the grasp.

Given U, we can analyze if the grasp is in stable equilibrium. In order to do this, Nguyen first identifies the equilibrium state which, following Fearing's first condition (Equations 13 and 14), is where the sum of all forces and moments in the grasping plane is zero. This is equivalent to the first partial derivatives of the potential function $U(x,y,\theta)$ being all zero, or:

$$\begin{cases} \left.\dfrac{\partial U}{\partial x}\right|_{(0,0,0)} \sum_{i=1}^{n} k_i\sigma_{io}\cos\alpha_i = 0 \\ \left.\dfrac{\partial U}{\partial y}\right|_{(0,0,0)} \sum_{i=1}^{n} k_i\sigma_{io}\sin\alpha_i = 0 \\ \left.\dfrac{\partial U}{\partial \theta}\right|_{(0,0,0)} \sum_{i=1}^{n} k_i\sigma_{io}\mu_i \qquad = 0 \end{cases} \tag{22}$$

This is equivalent to Equation 4.

Secondly, Nguyen evaluates the potentional function using the Taylor expansion about the equilibrium state as follows:

$$U(x,y,\theta)=\sum_{i=1}^{n}\frac{1}{2}k_i\sigma_{io}^2+\mathbf{x}^T\nabla U\big|_{(0,0,0)}+\frac{1}{2}\mathbf{x}^T H\big|_{(0,0,0)}\mathbf{x}+\ldots \tag{23}$$

where $\mathbf{x} = (x,y,\theta)^T$. In order to determine if the grasp is in stable equilibrium, we look at whether it is stable and also whether it is in equilibrium. As we saw, in order for the grasp to be in equilibrium, the gradient $\nabla U|_{(0,0,0)}$ must be zero (Equation 22). The grasp is stable if and only if the potential function $U(x,y,\theta)$ reaches a local minimum. For this, the Hessian matrix $H|_{(0,0,0)}$ must be positive definite. This latter is true if and only if all its principal minors are strickly greater than zero. Its first two principal minors are always strictly positive, but there are two special cases for the third one. It is strictly positive if the compliance center[16] is at the common intersection of the lines of action of the springs. It is also strictly positive if the compliance center is such that the weighted sum of the virtual springs is zero.

Nguyen (1987a) showed stable grasps in three dimensions using soft finger contacts. While point contacts without friction were modelled as one linear spring, soft finger contacts are modelled as four springs. This system included three linear springs through the point of contact that are oriented along the normal and along two tangential directions to the surface contact, and one angular spring, with axis going through the contact point that is oriented along the normal of the contact surface. "With soft fingers, the larger the friction cone, the more likely the grasp is force closure. This is why people tend to grasp at sharp corners and edges (if parallel surfaces are not available)." (Nguyen, 1987b, p. 241).

6.4 Force Application in Human Pad Opposition

6.4.1 Quantifying grip and load forces in pad opposition

In an elegant series of experiments, Westling and Johansson have investigated the force application in grasping (Johansson & Westling, 1990; Johansson & Westling, 1984b; Westling, 1986; Westling & Johansson, 1984). Subjects grasped objects of varying weights (200, 400, or 800 grams) and surface textures (silk, suede, sandpaper) using pad opposition between the index finger and the thumb. The test object had force transducers placed as indicated in Figure 6.16, providing measurement of grip forces for the thumb and index fingers, and the load force (or vertical lifting force). An ultrasound transducer and accelerometer measured object position and acceleration respectively.

Manipulations of object weight affected both the load force and

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[16] The center of compliance is the point of rotation of the planar object.

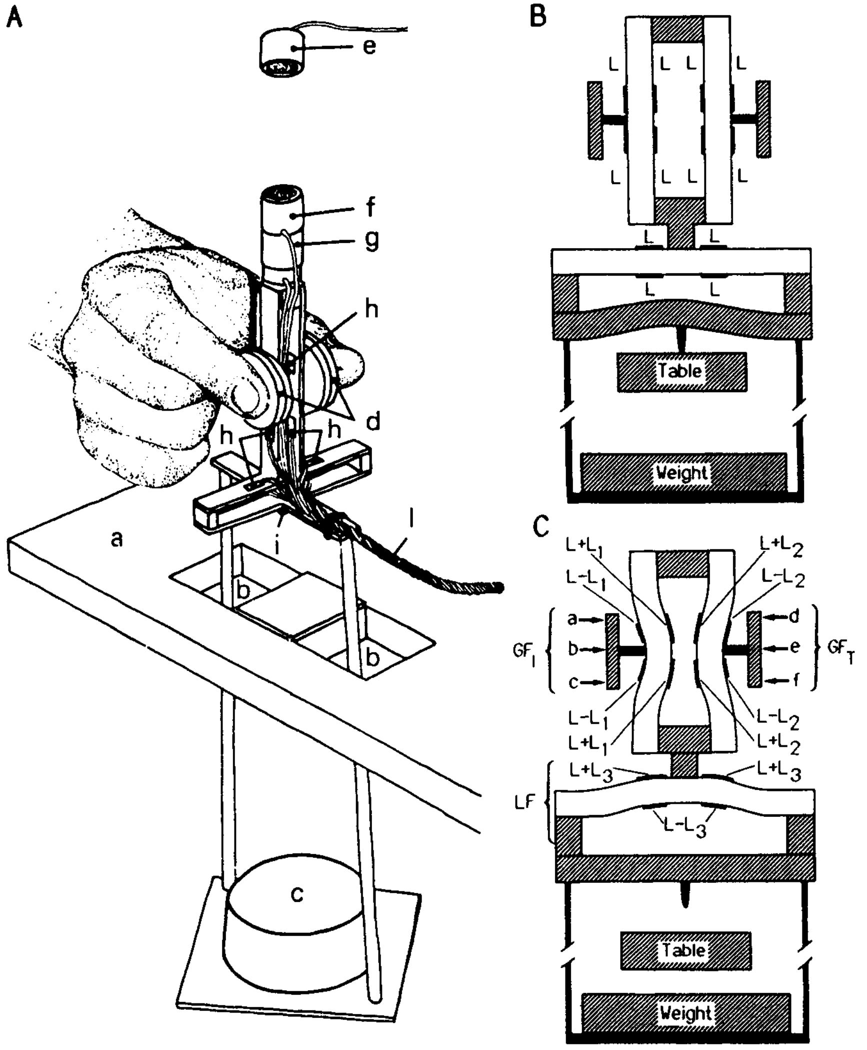

Figure 6.16 A. A schematic drawing of the apparatus used by Westling and Johansson. a - table; b - holes in table; c - exchangeable weight shielded from the subject's view by the table; d- exhangeable discs which constituted the touch surfaces; e and f- vertical position transducer with an ultrasonic receiver (e) and an ultrasonic transmitter (f); g - accelerometer (10-600 Hz); h - strain-gauge force transducers for measurement of grip force and vertical lifting force also denoted load force (dc -120 Hz); i - peg having a hemispherical tip on which the object rests while

the grip force, with a constant ratio of grip-force/load-force for a given surface texture. With heavier objects, lifting forces were applied for a longer duration, and at a higher rate. In contrast, manipulations of surface texture affected only the grip force, not the load force, thus different ratios of grip-force/load-force were obtained for a given weight (Johansson & Westling, 1984a, 1990; Westling, 1986). Thus, the surface texture manipulations affecting the frictional conditions in relation to the skin created a need for subjects to grip more forcefully a more slippery object, in order to achieve the same load force. These effects are shown in Figure 6.17.

Westling and Johansson (1984) showed how:

> "the static grip force is adapted to the friction between skin and object as well as to the weight of the object so that the employed grip force is greater by a relatively small safety margin than the minimal force required to prevent slip. The adaptation to the frictional condition appears to be dependent on signals in afferents terminating in the fingers, most likely tactile afferents, since it was impaired during blockage of the afferent signals in the digital nerves."

The coefficient of static friction with respect to the skin of sandpaper is higher than of silk (mean values reported by Johansson & Westling, 1984b, are 1.21, 0.68 and 0.35 for sandpaper, suede and silk

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standing on the table. To reliably define the point in time when the object took off from the table and when it made contact again, the contact with the table was electrically detected. B. and C. Illustration of the arrangement of the strain gauges and levers constituting the force transducers. Three groups of four strain gauges (with length = L) were glued to both sides of three levers (nonfilled in fig.). Each group constituted a full electric bridge measuring the load force and the two grip forces, respectively. B. The object with unloaded transducers rests on the table. C. Loaded transducers while the object is lifted. The initial length of the strain gauges are labelled L, and the lengths after loading L + Ln; and L - Ln (n=1, 2 and 3 for the three transducers respectively). Two of the strain gauges in each group were lengthened whereas two were shortened. Because the load force bridge was balanced when the object freely rested on the table, all load forces at the touched surfaces were reliably measured (from Westling, 1986; reprinted by permission from Johansson & Westling, 1990).

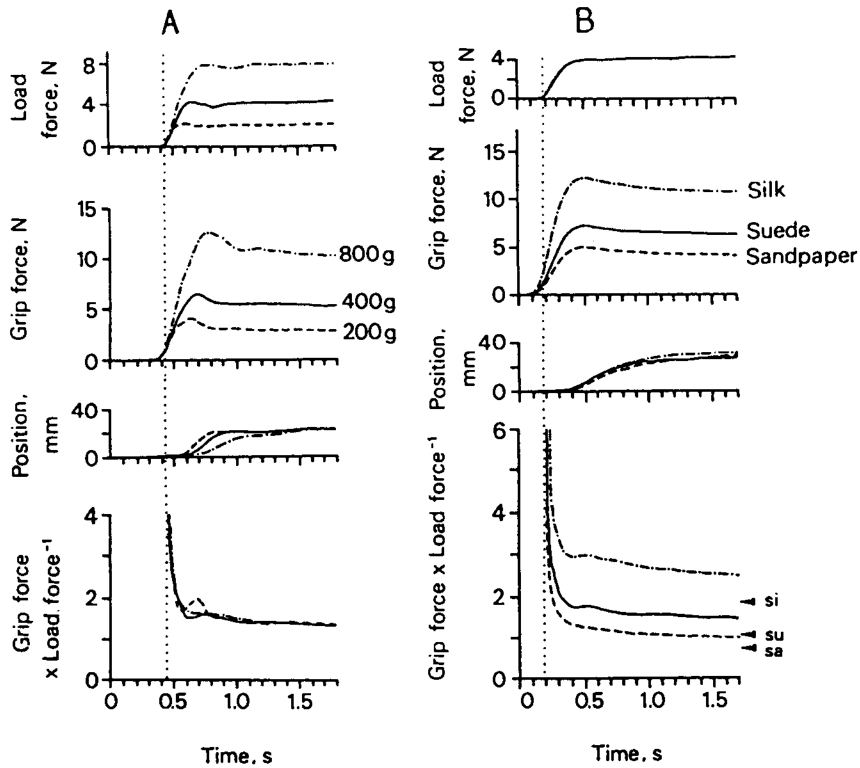

Figure 6.17 Force coordination during the initial part of lifing trials. Load force, grip force, vertical position and ratio between grip and load force are shown as a function of time. (a) Influence of different weights: 800g, 400g and 200g. Constant suede surface structure. Average data from 24 trials (single subject). (b) Influence of different surface structures: finely textured silk-most slippery, suede-less slippery, and sandpaper-least slippery. Weight constant at 400g. Average data from 120 trials (9 subjects). In both a and b, arrows indicate mean-slip ratios for the three structures. Illustrations represent standardized conditions in which the previous trials were carried out with the same weight and friction, respectively (from Johansson & Westling, 1984b; reprinted by permission from Johansson & Westling, 1990).

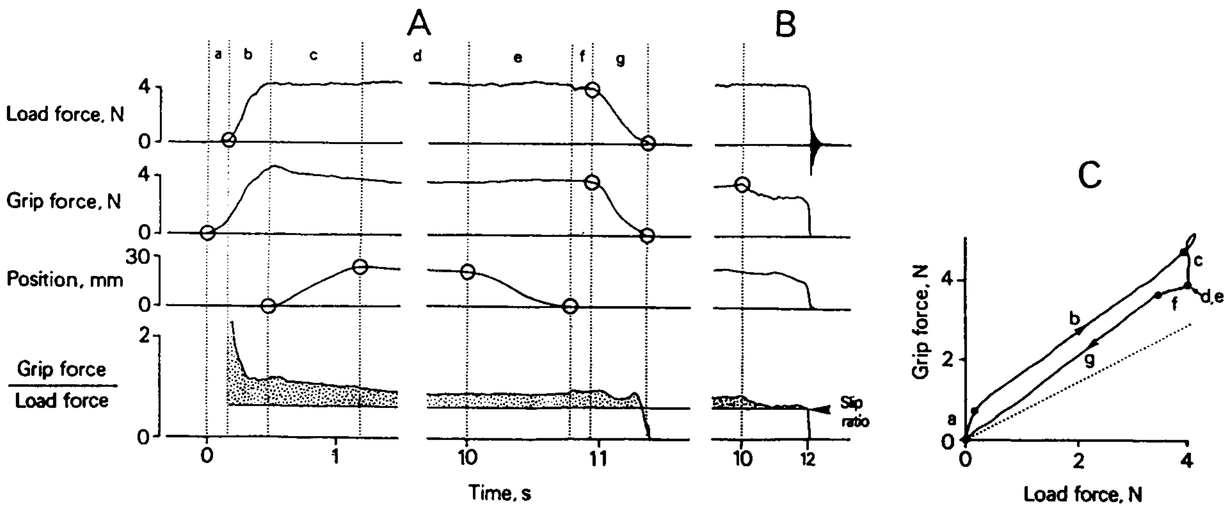

Figure 6.18 The principal phases of a lifting trial. Note the time scale is interrupted. A. Load force, grip force, vertical position of object and ratio between grip and load force as a function of time for a sample trial (weight 400 g, surface structure sandpaper). The periods indicated are: a - preload phase (increase of grip force from initial contact until object is securely grasped); b - loading phase (parallel isometric increase of the forces); c - transitional phase (while the object is elevated); d - static phase (the object is held stationary in space); e - replacement phase; f - delay; g- unloading phase (parallel isometric decrease of the forces). B. Slip ratio measurements at the end of a separate trial subsequent to the trial in A by asking the subject to hold the object in air and decrease the grip force until slips occurred. The vertical dashed line in B indicates the start of a slow voluntary grip force decrease. Horizontal dashed lines in A and B indicate the slip ratio obtained, and the shaded areas indicate the safety margin used to avoid slip. C. Grip force as a function of load force for a lift similar to A. Phases are as in A. The dotted line indicates the slip ratio (from Johansson & Westling, 1990; reprinted by permission).

respectively). Thus, the ratio of grip-force/load-force can be lower for sandpaper than silk for a given weight. The ratio of grip-force/load-force always exceeds a slip ratio by some safety margin. The slip ratio is that ratio of grip-force/load-force at which the object slips from grasp as subjects open their fingers, shown in Figure 6.17b. The grip and load forces and their ratios are shown for the entire duration of the task in Figure 6.18.

6.4.2 Phases in applying grip and load forces

Westling and Johansson identified a series of distinct phases for the task of lifting the object from a table, holding it in the air, then replacing it on the table. From Figure 6.18, they identified the following events. A preload phase (about 80-100 ms) as the subject first grips the object (a) during which the grip force increases but the load force does not. This is followed by a **load phase** (b) when the grip and load forces increase in parallel. When the load force overcomes the force due to gravity (equal to the weight of the object), the object starts to move, beginning a transitional phase (c). When the object is being held in the air, the position of the object and grip and load forces are nearly constant, comprising a static phase (d). The replacement phase (e) includes motion of the object back to the table. After a short delay phase (f), the **unloading phase** (g) occurs as the grip and load forces decrease in parallel. Then, the object is released.

Using a similarly instrumented dowel, many of the Johansson and Westling results have been replicated in experiments examining object weight and task requirements (Weir, 1991; Weir & MacKenzie, 1993, in preparation). We did not find a separate preloading phase; at first contact with the object, our strain gauge transducers register both grip and load forces. This may be reflecting minor differences in the object instrumentation or experimental setup. The Weir & MacKenzie experiments used a strain gauge transducer design similar to that in Figure 6.16. Our dowels were weighted with buckshot inserts below the transducing mechanism, whereas Westling and Johansson had their weights suspended from the instrumented object, below the table surface. Initially in the loading phase, the load forces were sometimes negative, indicating that subjects were 'pushing' the dowel into the table surface prior to liftoff, as shown in Figure 6.19. This increased with object weight such that heavier objects were pushed harder into the table as forces were first applied, prior to the parallel increase in grip and load forces. During the loading phase, for heavier compared to lighter objects, forces were applied for a longer duration, and at a higher rate, replicating Johansson and Westling. Peak grip and load forces were achieved after liftoff, i.e., after the object broke physical contact with the supporting table surface.

In marked contrast to the effects of dowel weight during the loading phase, Weir (1991) found that during the unloading phase, after (re)placement of the dowel, the rate of decrease of grip force increased with object weight, mirroring the effects during the loading phase. At the end of unloading and prior to release, subjects again pushed the object into the table, only with a greater load force for the lighter dowels (66 g dowel: -0.65 N, 155 g: -0.55 N) than for the heavier dowel (423 g: -0.3 N). This may be reflecting the need to stabilize the lighter object as it was replaced onto the table.

As well as the forces described above, Johansson and Westling measured single tactile afferent units (using microneurographic methods, after Vallbo & Hagbarth, 1968) and surface electromyography. Of interest is their conclusion that Type I units monitor the frictional demands for modulation of the grip during interaction with the object. Johansson & Westling (1990) summarized 3 sets of evidence indicating that tactile afferents having endings in the area of manipulative contact (Type I) are essential for proper adaptation of the grip force/load force ratio to the friction between the object and skin surfaces. They found: (1) when afferent signals were abolished by local anaesthesia, adaptation failed (Johansson & Westling, 1984b, Westling & Johansson, 1984); (2) electrical stimulation of tactile afferents triggered changes in the grip force/load force ratio; and (3) signals in tactile afferents appeared well correlated with subsequent alterations in the grip force/load force ratio (Johansson & Westling, 1987, Westling & Johansson, 1987).

Johansson & Westling (1984b; 1990) further suggested that this tactile afferent information is necessary for the phase transitions in the sequential unfolding of the task. Table 6.3 indicates mechanoreceptive afferent unit activity at critical points in the lifting task. Frictional aspects (surface texture) appear to affect firing frequency, specifically of FAI units during the loading phase. Weight aspects are not reported to affect unit firing systematically. Included in the table are only reliable, obligatory responses, in the sense that mechanoreceptive tactile afferents appear to provide these functionally related responses consistently (Westling, 1986). Note that of the phases identified above, there are corresponding afferent impulses in FAI, SAI, and FAII units, not SAII units. Activity corresponding to transitions at contacting and releasing the object are found in all 3 unit types; in contrast, activity corresponding to transitions at object lift and replace

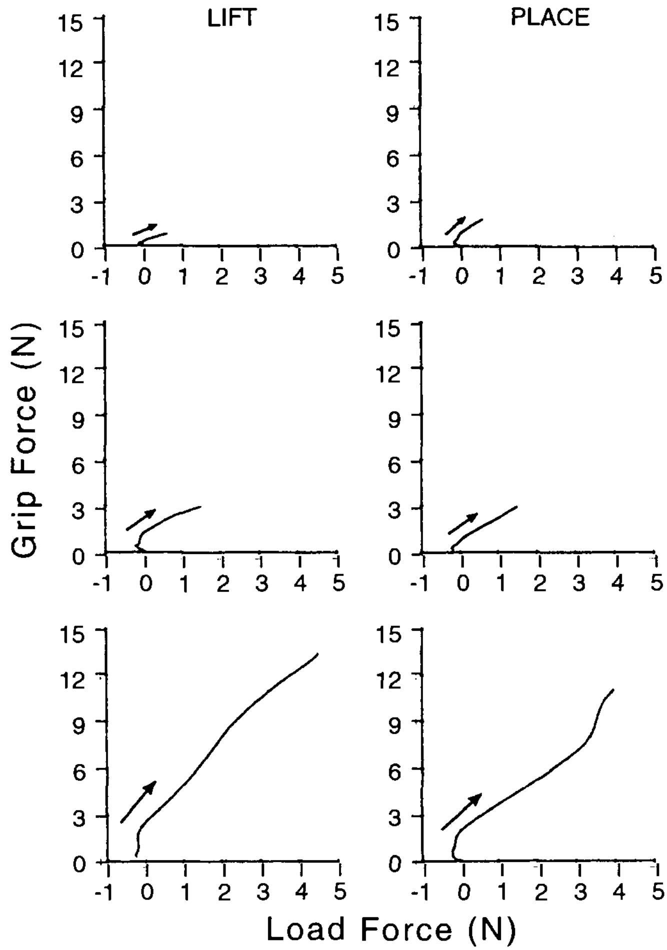

Figure 6.19 Grip force as a function of lift force during the loading phase, from dowel contact to dowel lift, for A) the 66g B) the 155g and C) the 423g dowels, for lift and place tasks. The arrow shows the direction of force change. Note at first contact, as grip force increases, load force decreases slightly, indicating that subjects are 'pushing' the dowel into the table. Grip force and grip force rate increased with object weight (from Weir, 1991; adapted by permission).

are found in only FAII units. Sometimes those having receptive field areas are distant from the fingertip areas in contact for the precision

Table 6.3 Summary of the activity of the four mechanoreceptive tactile afferent types (probable receptor morphology) during the grasp, lift and replace task of Johansson and Westling.

phase/ event	FAI (Meissner)	SAI (Merkel)	FAII (Pacini)	SAII (Ruffini)
preloading/ contact	-at contact -30-200 imp/s -friction affects frequency	at contact	at contact weaker than FAI	no response
terminate loading/ object starts to move	no response	no response	distinct bursts, even from wrist and palm fields	no response
holding	no response	some, irregular firing	no response	regular impulses. directional sensitivity to shearing forces
replacement ends/ object stops moving	no response	no response	distinct bursts, even from wrist and palm fields	no response
release	distinct burst	1/2 showed distinct burst	distinct burst, less reliable	no response
slips (see below)	distinct burst	distinct burst	distinct burst	no response

grasp. Recall that Babu and Devanandan (1991) found a high density of Paciniform corpuscles (FAII) in the ventral parts of the joint capsules of the phalangeal joints. The SAII units show three dimensional force sensitivity during holding. Johansson & Westling (1990) suggested that during manipulation, the population of SAII units may play a role in registering the magnitudes and directions of load forces and the balance between the grip forces and other manipulative forces. Responses from isotonic finger movements between the lifts, about 1 cm at the fingertips, were seen only in Type II units. The mechanoreceptive afferent information shown in Table 6.3 could be from the joint and muscle mechanoreceptors in addition to the cutaneous mechanoreceptors of primary interest to Johansson & Westling (1988a,b; Westling & Johansson, 1987).

The tactile afferent information from glabrous skin has been suggested as functional input for a neurally interfaced control system for the restoration of upper limb motor functions in quadriplegia or hemiplegia (Hoffer & Haugland, 1992). Such a closed loop control system could be used in combination with Functional Electrical Stimulation in paralyzed humans for transitions in these phases as humans make and break physical contacts with objects and supporting surfaces in the environment.

Johansson and Westling (1988b) reported EMG for elbow, wrist and hand muscles during the loading, transitional, and unloading phases of their lifting trials. These are shown in Figure 6.20. Several points are of interest here. First, note that during the loading phase in 'adequately programmed trials' (those trials where the weight to be lifted had been experienced in previous trials), all 4 pairs of antagonist muscles contracted together, 'providing the appropriate stiffness of the arm/hand system'. Second, although lifting (change in position of the object) may be due to motion about the elbow or wrist, none of the EMG values seemed to correlate with the motion of lifting the object. Third, on 'erroneously programmed trials' (e.g., lifts preceded by a heavier weight), termination of the loading phase was triggered by sensory signal related to the moment of lift off, associated with functional adjustments in EMG. When the lift occurred earlier than expected for the grip forces produced (i.e., lifts preceded by a heavier weight), somatosensory signals elicited by the start of movement triggered changes in the EMG of the intrinsic hand muscles in 100-110 ms and of the wrist and elbow muscles 20 ms earlier. For lifts erroneously programmed for a lighter weight (lift off doesn't occur when expected), the load forces are especially discontinuous, until the required load force is achieved. For the unloading phase, contact with the table triggered changes in the EMG of intrinsic hand muscles in 60-70 ms, and again 20 ms earlier for wrist and elbow muscles. Johansson and Westling attributed these changes associated with breaking and making contact with the table primarily to FAII units (Pacinian corpuscles), contrasting them with musculotendinous receptors. Pacinian corpuscles in the interphalangeal joints might be considered as possible candidates for this function.

For more detailed analyses of EMG activities during the dynamic phases of applying forces, we refer the reader to excellent references

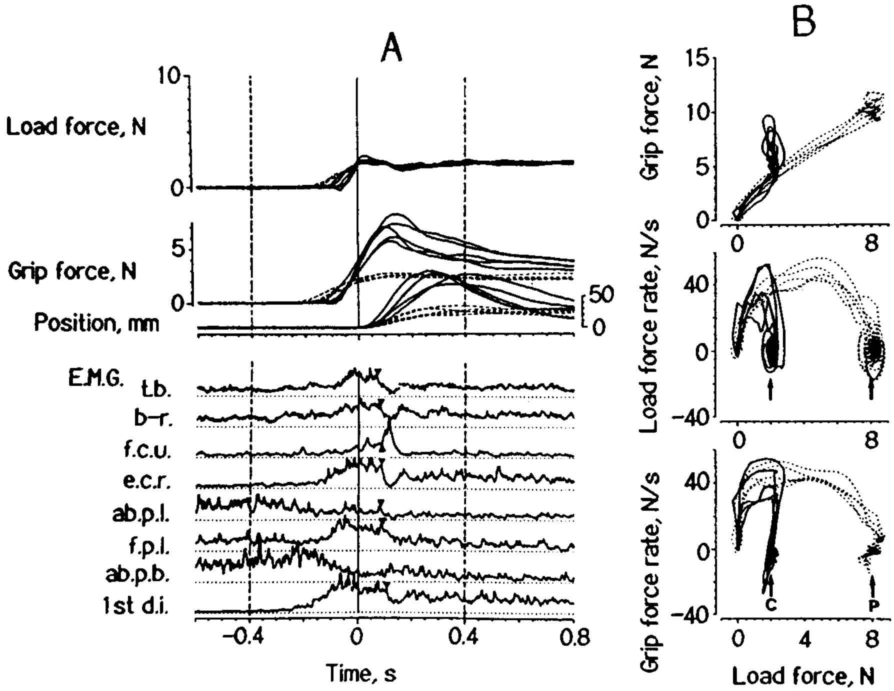

Figure 6.20 Initial parts of lifts erroneously programmed for a heavier weight. A. Load force, grip force, vertical position as a function of time for 5 lifts with 200g programmed for 800 g (solid line) and for 5 adequately programmed 200g trials (dashed line). Note the pronounced overshoots in the grip force and position signals for the erroneously programmed trials. EMG signals refer to the erroneously programmed 200g lifts (average data). Arrows indicate points having fairly abrupt changes in the EMG signals. Trials are synchronized in time at the moment the object started to move (time=0). B. Grip force, load force rate, and grip force rate displayed in relation to the load force for erroneously programmed trials in A (solid line) and for adequately programmed 800g trials (dashed line). Arrows labelled C and P indicate the load force at which the object started to move in the current and previous trial, respectively (from Johansson & Westling, 1990; reprinted by permission).

by Bronks and Brown (1987), Long (1970), Long, Conrad, Hall and Furler (1970) and Maier (1992). For analysis of the relationships among EMG, isometric grip forces, cortical and subcortical structures, see Hepp-Reymond (1991), Hepp-Reymond, Wannier, Maier and Rufener (1989), Lemon, Muir and Mantel (1987), Muir and Lemon (1983), Smith (1979, 1981), Smith, Frysinger, and Bourbonnais (1983). As an example, Smith (1981) provides evidence that the cerebellum plays an important role in switching between reciprocal inhibition and coactivation of antagonist muscles in the hand during grasping.

6.4.3 Slips, perturbations and magnets

In Westling and Johansson's task, slips were rarely visible or noticed by the subjects, but were inferred from accelerometer records. Corresponding afferent slip responses were reliably observed from FAI, FAII, and SAI afferent units, and were reliably absent from SAII units. Occasionally, even in the absence of accelerometer evidence, slips were inferred based on mechanoreceptive afferent activity in SAI and FAI units when the grip-force/load-force ratio was dangerously near the slip ratio. These were called localized afferent slip responses. Johansson and Westling (1987) noted that 10% of the afferent slip responses in FAI and SAI units occurred prior to overt slips causing accelerometer responses. Functionally, these slips resulted in a consistent upgrading of the grip-force/load-force ratio, to ensure stability. The latency between slip onset and the 'automatic' changes in the force ratio were between 60 and 80 ms with a mean of 74 (± 9) ms. Interestingly, similar to the phase dependence of cutaneous input during postural and locomotor activities, there is a phase dependent contribution in grip and load forces to this upgrading of the force ratio. During the loading phase (while the object is still supported by the table), changes in the load force rate were involved, whereas during the static phase (while the object is held stationary in the air), the grip force increased to a higher stable value (Johansson & Westling, 1990).

In Chapter 5, the effects of visual and mechanical perturbations on arm movement and hand configuration during the free motion phase were examined. Similar experiments have been conducted during a grasping trial, perturbing the vertical load force of objects. Cole & Abbs (1988) showed that rapid, unexpected increases or decreases in object load force (trapezoid pulse: 15 ms ramp, 50 ms duration, increase of about 2.5 N to a 0.7 N object) bring about corresponding increases or decreases in grip force with a latency of 60 - 90 ms with a mean of 74 (± 11) ms. Phasic EMG bursts occurred

50 - 70 ms after onset of load force perturbations, with a silent period preceding the phasic burst, 30 - 40 ms after perturbation onset (in all muscles recorded except extensor digitorum communis). Note the similarity in latency to the 'automatic' adjustments in the grip-force/load-force ratio to slips reported by Johansson and Westling (1988a). Subjects never made an error in the direction of the automatic, short latency, response, e.g., a rapid increase in load force always yielded an increase in grip force. The increase in grip force averaged 7.2 (± 2) N and was within 6 - 10% of the grip force needed to lift the object. In contrast to the sustained response to object slip, the grip force in response to load perturbation steadily decreased (to the level necessary to maintain grasp). The grip force response to perturbation was sensitive to the size and velocity of the load force increase but not the preexisting grip force; thus, Cole and Abbs concluded that the grip force was at a level to maintain grasp, i.e., proportional to the required load force, not at a specified level above the object's slip point. They note the impairment with digital anesthesia, and consider the role of cutaneous, joint and muscle mechanoreceptors in signalling the load changes, with emphasis on cutaneous mechanoreceptors detecting shearing forces on the skin of the finger pads.

Johansson and colleagues (Johansson et al., 1992a,b,c) performed a series of load perturbation experiments, using pad opposition. In the absence of instructions to initiate grip changes, they showed that the latency of the initial grip force responses, termed 'catch-up response' was dependent on load force rate (e.g., 80±9, 108±13, 138±27 and 174±39 ms for the 32, 8, 4, and 2 N/s rates respectively). The latency of grip force response to different loads (with a constant load force rate of 4 N/s) was 140 (±30) ms. The amplitude of the grip force response was a function of both load force and load force rate, but its time course was similar over all rates of perturbing load force. For longer lasting loading phases, the catch-up response was followed by a 'tracking' response, in which grip force increased in parallel with load force, to maintain a slip ratio. Interestingly, with digital anaesthesia, subjects had to voluntarily attend to the task (usually automatic, without anesthesia), the grip force latencies were prolonged (to several hundred milliseconds), with less modulation of grip force, absence of grip force responses (absent from 25 - 93% of trials, depending on subject), and there was a lack of dependence of the 'catch-up' grip force responses on load force rate. With digital anaesthesia, there were large individual differences, suggesting that for some subjects, more proximal mechanoreceptors might be mediating grip force responses. There was a lack of the 'tracking response' with digital anaesthesia as well, confirming the requirement of continuous afferent input from both thumb and index finger for grip force regulation in pad opposition. Contrary to their initial expectations, there appeared to be independent force control for each finger. The cutaneous strain at digital pulps resulting from increased shear forces was believed to be the most relevant mechanical stimulus of the digital mechanoreceptors. Johansson and colleagues also note extension of the interphalangeal joints and flexion of the metacarpophalangeal joint of the index finger as possible stimuli for mechanoreceptors, since these appeared to aid grip force modulation with digital anesthesia.

To investigate the influence of task instructions on loading or unloading perturbations, Winstein, Abbs and Petashnick (1991), prior to each block of trials, verbally told subjects to 'hold' or 'let go' in response to any apparent change in object weight. Thus they had a set to 'hold' or 'let go'. The latencies of evoked grip changes, with a mean of 66 (±13) ms and as early as 35 ms after perturbation onset, were unaffected by either instructions or direction of loading. Grip force responses to unloading were unaffected by instructions; in contrast, with loading, the magnitude of early grip responses were 27% higher following hold than following let go instructions. In hold conditions, the post-perturbation grip force level was sustained. In let go conditions, a second grip force response was observed with median latencies of 239-401 ms, across subjects. The latency of the let go response did not vary with unloading or loading conditions. They noted that the magnitude of the grip force responses were much more marked (on average 3.6 times higher) to loading than unloading forces of equivalent magnitude, suggesting this reflects functional evolution of the hand in a gravity dominant world. Winstein et al. note the importance of balancing two functional goals: first, to ensure the object is not dropped or to maintain the object in stable grasp (not too little gripping force) and second, to ensure the object is not crushed or broken (not too much gripping force).

In determining the slip ratio in pad opposition, during the time when individuals tried to voluntarily release their grasp, they felt as if their fingers adhered to the object (Johansson and Westling, 1987, 1990). It is as if the cutaneous afferents and peripheral biomechanics to grasp are in contradiction to the efferent commands to release. The effort required to overcome this <u>magnet phenomenon</u> was greater using sandpaper as the surface structure, and became stronger as the grip force approached the minimum grip force to prevent slips. They suggested that the automatic regulatory processes to maintain a safety margin (a grip force/load force ratio slightly above that for the slip ratio) interfered with the drive to decrease the grip force voluntarily. Even during the period of releasing forces, slip responses were seen. Interestingly, in contrast to ordinary slip responses, these slip responses did not result in maintained change of the force balance. "Thus the voluntary command to separate the fingers appeared to selectively suppress one component of the motor response, that is, the maintained, memory-based upgrading of the grip force. That an early brief force response still remained suggests that two different CNS mechanisms mediate the motor response to slips" (Johansson & Westling, 1990, p 707).

The magnet phenomenon could be also reflecting the fact that adherence to papillary ridges increases as grip force decreases. The lubricant secreted through the tops of the papillary ridges is greasy, having high adhesive qualities at low shear velocities and lower adhesive qualities at high shear velocities (Moore 1975). Past researchers had attributed the magnet effect to vibration effects on muscle spindles' afferent activity. Torebjörk, Hagbarth & Eklund (1978) showed that the magnet reaction, in which the fingers tend to adhere to a vibrating object and there is difficulty in loosening the grip, is attributed to a reflexive response to the excitation of the mechanoreceptors in the fingers, not to vibration of the muscle spindles in the finger flexor muscles.

6.4.4 Object shape and contacting area: Geometry of contact

In comparing pad opposition using different shaped dowels, Weir (1991) noted differences between a dowel instrumented for transducing grasping forces, with flat, parallel square gripping plates, and a cylindrical dowel. Both dowels had the same available surface area for grasping and 1.5 cm between the grasping surfaces, i.e., the magnitude of the opposition vector was 1.5 cm. An analysis of the elliptical fingerprints made by the thumb and index finger in pad opposition yielded striking differences between the two dowels. When grasping the flat, parallel plates, the surface area contacted was substantially greater than when grasping the cylindrical object. Further, the orientation of the elliptical contacts made by the thumb and index finger differed. For the cylindrical dowel, the long axis of the ellipse was oriented about the transverse plane of the finger and long axis of the dowel; in contrast, for the parallel plated dowel, the long axis was oriented about the sagittal plane of the finger, and horizontally on the short axis of the dowel. When the surface area actually contacted was equated between the two dowels through experimental manipulation, the differences between the two dowels disappeared. Thus, dowel shape affected the surface area actually contacted; the surface area actually used was the important variable, not shape per se.

6.5 Force Application with Other Oppositions

6.5.1 Measuring forces

It was noted that one of the functions of the hand in prehension is to apply forces to match the anticipated forces in the task. One measure is to examine the maximum forces that can be exerted using the different types of grasps. In their biomechanical studies of functional strength assessment, Chao and colleagues (Chao, An, Cooney & Linscheid, 1989) determined the maximum forces that could be exerted using tip pinch (compressive force in pad opposition between the tip of the thumb and index), pulp pinch (compressive force in pad opposition between the pulps of distal phalanx of the thumb and index), key pinch (side opposition applied by the thumb pad through the lateral aspect of the distal interphalangeal joint of the index), and power grip (palm opposition centered on the middle phalanx of the middle finger, with the thumb wrapped around). Using specially designed strain gauge instruments, they adjusted for individual differences in hand size, shapes, deformations, etc, in order to standardize the results. Table 6.4 summarizes their results, based on 124 adults, and 32 patients with documented single nerve lesions of the radial, median and ulnar nerves. Consistent with the suggestions above, palm opposition generates the greatest gripping forces, pad oppositions generate the least; and side opposition is intermediate. Note also that for normals, little difference exists between the tip pinch and the pulp pinch in the maximum compressive force.

Information about the maximum grip forces that can be exerted using the different grasp types is valuable and useful as a way to identify a physical constraint on a selected posture. However, forces applied during prehension are usually at levels below maximum grip force. In addition, the hand's configuration will factor into this, and grip force will be affected by the number of fingers participating in the grasp.

Table 6.4 Functional strength (kg) of neuropathic patients and normals using different grasp types. Mean strength for a larger group (and standard deviation in parenetheses) are shown for 65 men and 59 women. Neuropathic patients have ulnar, median or radial nerve lesions (from Chao, An, Cooney & Linscheid, 1989; adapted by permission).

neuropathic (lesions)	power grasp	tip pinch	pulp pinch	key pinch
ulnar (n=14)	18.5	2.8	2.4	4.9
median (n=13)	20.1	4.2	4.2	7.6
radial (n=5)	14.0	3.2	4.0	7.1
normal (n=46)	34.6	5.6	5.1	9.8

normal	power grasp n=60	tip pinch n=124	pulp pinch n=60	key pinch n=84
males	40 (9)	6 (1)	6 (1)	11 (2)
females	23 (7)	5 (1)	5 (1)	8 (1)

Another physical aspect of applying forces is the direction of the force application. Using a task involving an isometric palm opposition on cylinders, Amis (1987) studied the effect of object size on force application. Amis computed the total normal force (gripping) applied by the four fingers and also the shearing force (pushing or pulling) at the phalanges. He determined that the distal phalanx exerts the largest gripping force in all fingers. A smaller force was produced by the middle and proximal phalanges. Summing up these forces within a finger, the total normal force was largest for the smallest objects, and then decreased as the object size increased. Shearing forces at the distal and proximal phalanges for the index, middle, and ring fingers tended to pull the object into the grasp for smaller objects. As the object got larger, shearing forces on the middle and proximal phalanges tended to zero out, while at the distal phalanges, shearing forces tended to push the object out of the grasp.

Other object properties have an effect on force generation as well. Cochran and Riley (1986) found that handle shape affects the force exerted: higher forces were seen with irregularly shaped handles (rectangular and triangular) than with uniformly shaped ones (circular).

Napier pointed out that the wrist posture is different in a power grasp vs a precision grasp. In the power grasp, the wrist is positioned with ulnar deviation, neutral between extension and flexion, whereas in a precision grasp, the wrist is dorsiflexed, positioned between ulnar and radial deviation. Because the extrinsic muscles send tendons through the wrist, the amount of force that the fingers are able to apply is greater in wrist extension and/or ulnar deviation than in other positions. In addition, there are differences between the fingers in their potential contribution to force application. For a hook grip, Hazelton et al. (1975) noted that the relative amount of force available at each finger remains constant across wrist positions (25% at the index, 33.5% at the long finger, 25% at the ring finger, and 16.5% at the little finger). For the power grasp, Amis (1987) found the mean contributions to the overall grasp force to be 30%, 30%, 22%, and 18% for the index, long, ring and little fingers, respectively.

The human hand can impart arbitrary forces and torques using pad opposition in the tripod (Drucker & Hollerbach, 1987). Subjects grasped a medium sized sphere using the thumb, index and middle fingers. The sphere was instrumented with a sensor capable of measuring forces and torques along six axes. Receiving constant feedback about actual forces being applied, subjects were asked to manipulate the sphere in arbitrary directions in order to achieve a target. Results indicated that subjects could control all force and torque components separately.

6.5.2 Analytic posture measures

The analysis of a grasp in the field of robotics uses formal quality measures. A formal quality measure is a quantification of some aspect of a grasp posture. Cutkosky and Howe (1990) informally described these measures as follows:

Compliance: what is the effective compliance (the inverse of stiffness) of the grasped object with respect to the hand?

Connectivity: how many degrees of freedom are there between the grasped object and the hand?

Force closure: assuming that external forces act to maintain contact between the fingers and object, is the object unable to move without slipping when the fingers are 'locked'?

Form closure: can external forces and moments be applied from any direction without moving the object when the fingers are locked?

Grasp isotropy: does the grasp configuration permit the finger joints to accurately apply forces and moments to the object?

Internal forces: what kinds of internal grasp forces can the hand apply to the object?

Manipulability: can the fingers impart arbitrary motions to the object?

Resistance to slipping: how large can the forces and moments on the object be before the fingers will start to slip?

Stability: will the grasp return to its initial configuration after being disturbed by an external force or moment?

These quality measures can be applied to the human hand (Cutkosky & Howe, 1990). All grasps except the gravity dependent ones satisfy force closure, in that they can control internal forces and apply positive and negative forces to counteract external forces. The non-clamping ones satisfy force closure as long as external forces do not cause the fingers to detach from the object (e.g., a tray does not start rising against gravity). Many grasps do not satisfy form closure without friction, meaning that they do not form a complete kinematic constraint around the object. Instead, the direction of task forces are anticipated and postures are chosen to counteract only those. Examples of force closure without form closure include pulling on a large wrench to loosen a bolt with a hook grasp or holding a screwdriver in pad opposition while pushing down on it. Assumptions are made that the wrench will not pull away from the hand and that the screw will never pull on the screwdriver.

Table 6.5 summarizes Cutkosky and Howe's analysis of pad versus palm opposition. Pad opposition has a high manipulability measure, isotropy, high compliance, low stability, low resistance to slipping, satisfies force closure, and a connectivity of at least three degrees of freedom. In English, this means that the fingers can impart arbitrary motions to the object and accurately apply the forces and moments, along at least three degrees of freedom. No expected external force and moment will move the object out of the posture, but large external forces will cause the object to slip, and if disturbed, the posture will not return to its initial configuration. With high compliance (low stiffness), fingers can move rapidly and still minimize any potential danger to the fingers or object; colliding with surfaces will cause deflection, instead of damage. A compliant grasp is more sensitive to small changes in force. In contrast, palm opposition satisfies form and force closure, is less compliant, more stable and has a larger resistance to slipping than precision grasps. As well, palm opposition has a connectivity of zero and a low manipulability measure. In English, this means that the object is fixed

Table 6.5 Summary of Cutkosky & Howe (1990) description of pad and palm oppositions in terms of analytic measures from the field of robotics.

Grasp type	Value of analytic measure	English Meaning
Pad opposition	High manipulability	Fingers can impart arbitrary motions to the object
	High isotropy	Fingers can accurately apply forces and moments to object
	High compliance	Minimize danger to fingers and object by using force control in response to perturbations
	Connectivity $\geq$ 3 dfs	At least 3 dfs exist between object and hand
	Satisfies force closure	Assuming fingers will maintain contact with object, fingers can resist arbitrary forces and moments
	Low stability	After disturbance, fingers will not return to initial position
	Low resistance to slipping	Fingers cannot resist external forces without slipping
Palm opposition	Satisfies form closure	No external arbitrary forces and moments can move object
	Satisfies force closure	Assuming hand surfaces will maintain contact with object, fingers can resist arbitrary forces and moments
	Low compliance	Minimize 'give' in collisions with environment, using position control in response to perturbations
	High stability	After disturbance, fingers will return to initial position
	High resistance to slipping	Large forces and moments are needed in order to make object slip
	Connectivity = 0	No degrees of freedom between object and hand
	Low manipulability	Fingers cannot impart arbitrary motions to object

in the hand and it cannot be moved. Very large forces are needed to make the object slip, and if external forces try to move it, the posture will return to its configuration. With low compliance (high stiffness), colliding with external surfaces will have little 'give', thus providing a method for transmitting forces from the arm through the object (e.g., hitting a nail with a hammer, etc).

6.6 Moving a Grasped Object: Transporting, Twiddling, and Twirling

In this section, we focus on the subgoals of holding, transporting, manipulating and placing, considering experimental and analytic approaches.

6.6.1 Manipulation by humans

In acquiring an object into stable grasp, the system being controlled changes from the hand to the hand plus object. The object becomes an extension of the hand (Polanyi, 1958), and the new

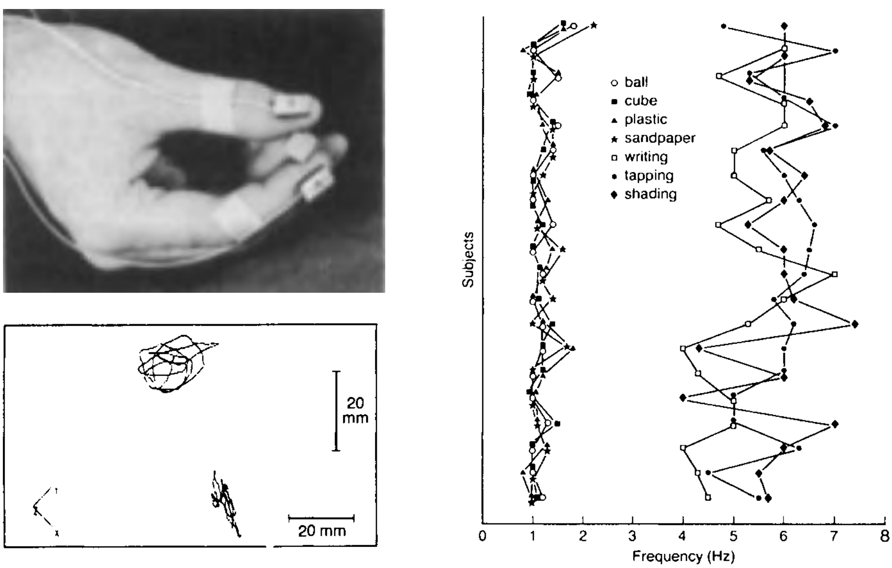

Figure 6.21 Distribution of temporal frequencies obtained for active touch, or exploratory tasks (tactile discrimination of ball and cube shapes, or plastic and sandpaper textures) are clustered from 1 - 2 Hz, whereas the frequencies for performatory movements like (writing, tapping and shading) cluster from 4 - 7 Hz. The role of sensory information in motor control is fundamentally different for exploratory and performatory movements, consistent with the work of Gibson (1962) and Lederman and Klatzky (1987). (from Kunesch, Binkofski and Freund (1989); reprinted by permission).

system has a different set of mechanical and functional properties. Once grasped, the object is lifted, and it may be held (as in lifting a mug to wipe a countertop), transported (to place the mug on a shelf), manipulated (to hand to someone, to drink from, or to explore its features) and replaced (on the countertop).

In considering manipulative hand movements, a profound distinction was made by Kunesch, Binkofski and Freund (1989). They analyzed the temporal frequency characteristics of manipulative, serial hand movements, for tasks including tactile discrimination, pencil shading, handwriting, typewriting, and repetititive tapping. They report a bimodal result: two separate classes of natural preferred frequencies (see Figure 6.21). At 1.56 Hz cluster exploratory finger movements in which the hand is used in active touch, to determine object properties like shape and texture. They suggest the slower range reflects 'focal sensory control', i.e., the temporal requirements of the sequential sampling from the mechanoreceptor population. These movements use motion to collect detailed somatosensory information. At 4 - 7 Hz cluster handwriting, and other cyclic, learned hand movements, with frequencies close to those of fast tapping. Frequencies for handwriting and shading were almost the same, regardless of whether the fingertip or pencil was used. They suggested the higher frequency movements are under different sensory control: the high frequency movements are not performed entirely open-loop, but monitored by 'preattentive sensory processes'. These movements use proprioceptive and somatosensory inputs to monitor motion. This distinction between the two types of movements, consistent with Gibson's (1962) 'exploratory' and 'performatory' hand movements, is important for several reasons. First, the role of sensory information in motor control is different in the two classes of movements. Second, the task requirements for manipulation are key inputs for control, and manipulation to extract object properties using active touch is fundamentally different from manipulation in using touch for action with objects.

It is important to distinguish between a static grasp for holding and transporting an object and a dynamic grasp for manipulation. In the first instance, an object is held firmly in a stable grasp with constant contacts, and object motion is achieved via the wrist, elbow, shoulder, or even through locomotion. In contrast, coordinated movements of the digits can manipulate an object within the hand.

With respect to humans transporting a grasped object, it was observed in Chapter 5 that the kinematics of pointing with a loaded limb (Atkeson and Hollerbach, 1985) are scaled from the trajectory of an unloaded limb, i.e., shape invariance in the velocity profile was observed. This finding has extended to transporting grasped objects of different weights. For pad opposition, investigating the effects of object weight (66, 155, and 423 g cylinders, of constant size and other visible characteristics) on kinematics and grip forces in a grasp to place task, Weir (1991; Weir & MacKenzie, 1993) found that during the dowel transport phase, maximum resultant velocity varied inversely with dowel weight, but the transport trajectories showed shape invariance, i.e., were scalable over time. In addition, a surprising, but robust kinematic finding, demonstrated by all subjects tested, was that during dowel transport, although the finger pads remained in contact with the gripping plates of a force transducer dowel, the aperture between thumb and index markers decreased substantially (about 15 mm), presumably reflecting finger posturing for force application and propulsion of the dowel forward towards the target location.

With respect to the forces applied during transport of a stably grasped object, Weir (1991) found that peak grip forces were higher when subjects transported the dowel to a target location 20 cm further forward in front of body midline (6. 0 N) than when they lifted the dowel to a 4 cm height (4.5 N). Peak load forces did not vary as a function of task requirements to lift or place, only as a function of object weight, replicating Westling and Johansson (1984; Johansson & Westling 1988a). In transporting an object, Flanagan, Tresilian and Wing (1993) concluded that the programming of grip force is part and parcel of the process of planning the loaded arm movement. Flanagan et al. studied point-to-point and cyclic movements of varying rates and directions and reported a tight coupling between grip and load forces; grip forces were modulated in phase with load force during movements with grasped objects. Flanagan et al. noted that the load forces varied both with the gravitational and inertial components.

In <u>dynamic grasping</u> four forms of manipulation can be considered:

1) **FIXED CONTACTS** - contacting locations between hand and object remain constant as motion is imparted to the object using coordinated manipulation.
2) **ROLLING CONTACTS** - contacting locations between hand and object roll past one another while imparting rolling motion to the object. Fingers can roll on object or object can roll in fingers.
3) **SLIDING CONTACTS** - contacting locations slide relative to one another imparting sliding motion to the object.
4) **REPOSITIONING OR REGRASPING** - motion is imparted to object by relocating the hand's contacting points on the object.

In classifying human hand movements, Elliott and Connolly (1984) identified 11 different dynamic movements. In order to describe the movements, the hand reference frame shown in Chapter 2 is recalled, as seen in Figure 6.22. Three axes are aligned with the palm of the hand, along anatomical directions. Oppositions occur along these axes. The pinch is a term used by Elliott and Connolly to describe movements towards and away from the palm, such as removing a splinter or manipulating a thread. As seen in Table 6.6, the movement translates the opposition vector of the object along the z (ventro-dorsal) direction of the hand while the object is grasped in pad opposition. The dynamic tripod, used for writing, combines pad and side opposition and translates the opposition vector mostly along the x (distal-proximal) axis. However, the side opposition between the

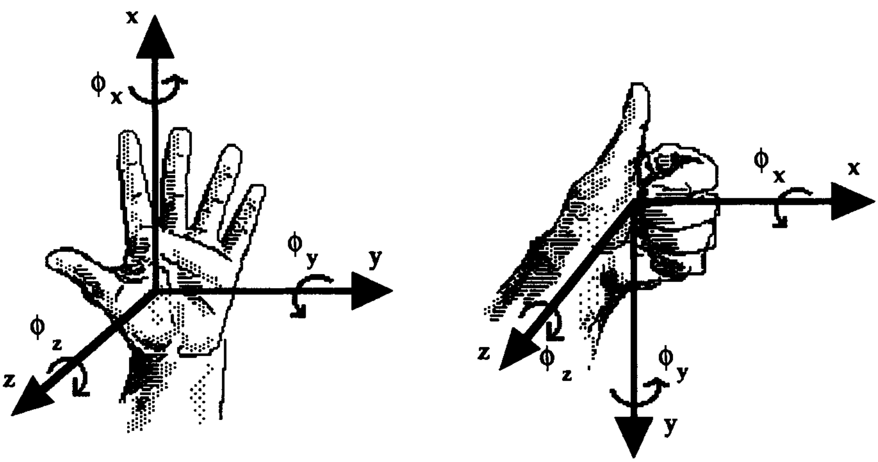

Figure 6.22 Hand coordinate frame for describing dynamic movements (from two perspectives). The x axis parallels the length of the palm in a distal-proximal direction. The y axis traverses the width of the palm in the radio-ulnar direction. The z axis is perpendicular to the palm in a ventro-dorsal direction. Pad opposition occurs along the x axis, side opposition occurs along the y axis, and palm opposition occurs along the z axis.

thumb and radial side of the middle finger adds the ability to translate the opposition vector along the y (radio-ulnar) axis. As can be seen in the table, rock, twiddle, and radial roll are all rotations of the opposition vector around the hand's z axis. The difference between them is in the oppositions being used, the relative motions of the fingers, and the length of the opposition vector. The radial roll is for very small objects, where side opposition is used and movement is generated by the index finger and while the thumb remains stationary. In twiddling, this is reversed (thumb moves, index stationary) so that alternating between pad and side opposition is exhibited. The rock movement is for larger objects, such as turning jar lids or coins. The squeeze motion, occuring in the x axis, does not cause movement of the opposition vector; instead, it changes the length of it, as in squeezing a syringe or a rubber ball. Finally, regrasping can occur if the fingers must be repositioned to repeat the movement in a sequential or phased way.

Elliott and Connolly (1984) also observed dynamic combinations of oppositions. The ulnar fingers could affix the object, or part of the object, in the hand, in palm opposition, while the radial fingers could perform a manipulation using pad opposition. An example is holding a string and tying a knot in it. Another combination is what they call the 'solo' use of a finger: an object, such as a cigarette lighter, is held in palm opposition, while the thumb, as a virtual finger three, strikes the lighter. One interesting pattern of dynamic movements that they observed is the palmar slide (see Table 6.6). Using palm opposition to hold part of the object, translation of the other part of the object occurs in the x-y plane using either pad opposition or a combination of pad and side opposition.

Table 6.6 could be viewed from a different perspective, so that the focus is not on the movement names, but instead on the functionality. This is similar to what was done in Appendix B for static postures. Besides the oppositions used and virtual finger mappings seen in the appendix, the dynamic function table for human hands would include the type of opposition vector transformation, direction of movement, and relative use of fingers, as outlined in Table 6.6. These, along with the length of the opposition vector, are a dynamic way to relate the motions needed in the task to the motions available to the hand, demonstrating Napier's conjecture that power and precision task requirements are met by the hand's power and precision capabilities (Napier, 1956).

Johansson and colleagues (Johansson et al., 1992a,b,c) made a contrast beween two types of purposeful grasping activities, manipulating 'passive' objects (to move or reposition mechanically predictable, stable objects like a mug) or 'active' objects (to manipulate mechanically unpredictable objects, like my dog's leash, when the dog is attached). They suggested that for mechanically predictable objects, we rely on sensorimotor memories, and motor output is based on anticipatory parameter control, i.e., we are using robust but flexible

Table 6.6 Elliott & Connolly (1984) dynamic hand movements organized according to contact forms. Each is described in terms of oppositions being used to hold the opposition vector. The type and direction of movement of the opposition vector relative to the palm is shown.

Form	Movement Name	Opposition	Direction of Movement	Relative motion of VFs	Example
Fixed contacts	Pinch	Pad	Translation along z axis	concurrent	removing splinters
	Dynamic tripod	Pad&Side	Translation along x axis some y axis	concurrent	writing with pen
	Palmar slide	Palm with either Pad or Pad&Side	Translation along x-y plane	concurrent	removing pen cap
	Rock	Alternate Pad and Side	Rotation about ϕz	concurrent	screwing a lid
Rolling contacts	Twiddle	Alternate Pad and Side	Rotation about ϕz	thumb moves, index fixed	screwing small nut
	Radial roll	Side	Rotation about ϕz	thumb fixed, index moves	winding a watch
	Index roll	Pad	Rotation about ϕy	concurrent	rolling up paper
	Full roll	Pad with 5 fingers	Rotation about ϕy	concurrent	rotating small mirror
Sliding contacts	Linear step	Pad	Translation along x-y plane	concurrent	climbing object
	Squeeze	Pad	Reduction about ϕz	concurrent	squeezing syringe
Regrasping	Rotary step	Alternate Pad and Side	Rotation about ϕz	concurrent	turning a dial
	Interdigital step	Alternate Pad and Side	Rotation about ϕz	concurrent	turning pen over

internal representations of the object's properties based on previous manipulative experiences. For passive, predictable objects, they suggested somatosensory afferent signals intervene only intermittently, according to an 'event driven' control policy. In contrast, for active objects, control of grip and other reaction forces rely more regularly on somatosensory input, due to the unpredictable and erratic physical characteristics of the object. Grip forces appeared to be automatically regulated according to variations in the amplitude and rate of imposed load forces. Further experimentation is needed to define the effects of shearing forces, other aspects of object unpredictability, and to extend the research which has focussed primarily on pad opposition.

6.6.2 Manipulation by robots

As noted in considering the functional demands on a hand posture, applying forces to stably grasp the object is separate from imparting motion to an object for manipulation or transportation. In robotics, various algorithms have been developed for modelling the grasping forces (the internal forces described in Section 6.3.1) from the manipulation forces (the forces that impart motion to the object). For example, Yoshikawa and Nagai (1990) identify internal forces using geometric characteristics for a three-fingered grasp with frictional, point contacts. The grasping force is defined as an internal force which satisfies the static friction constraint. It consists of the unit vectors directed between the contacts. Using these unit vectors, grasp modes are specified for grasping arbitrarily shaped objects. The manipulating force is then defined as a fingertip force which satisfies the following 3 conditions:

(1) it produces the specified resultant force;
(2) it is not in the inverse direction of the grasping force; and
(3) it does not contain any grasping force component.

The method of manipulation they analyze is fixed contacts, since point contacts with friction do not allow rolling or sliding at the contacts. They present an algorithm for decomposing a given fingertip force into manipulating and grasping forces (note that the analytic solution may not be unique because of the existence of multiple grasp modes).

Li and Sastry (1990) proposed a control algorithm for manipulation in two modes: fixed contacts and rolling contacts. Tasks are modelled as ellipoids in wrench space and twist space, with the shape of each ellipsoid reflecting the relative force requirement or motion requirement of the task. A grasp is stable if for every object wrench, there is a choice of joint torques to balance it, and a grasp is manipulable if, for every object motion, there exists a choice of joint velocities that will accommodate that motion without breaking contact. A grasp is assigned a twist space quality measure, which is the ratio between the task ellipsoid and the finger joint velocities, and a wrench space quality measure, which is the ratio between the task ellipsoid and the joint torques. A grasp is 'good', with respect to a given task, if it has a higher quality measure than other grasps (e.g., precision tasks need grasps with a high quality measure in the twist space). Finding a good grasp, then, is solved as an optimization problem. Once the grasp is found then given a goal, such as moving an object along a specified trajectory, Li and Sastry formulate a control algorithm for realizing the trajectory without breaking contact while regulating the internal forces.

Fearing (1990) discussed how Kobayashi (1985) used a force control system to control local object motions with fingers in constant grasping locations. When objects need to be regrasped, for example in twirling a baton, roboticists have accomplished this through preprogrammed finger position commands (Okada, 1982) or using a sequence of applied forces at each finger (Fearing, 1986). To ensure robust manipulation, tactile sensing and perception are needed to provide information on contact forces and local shape properties. Tactile sensors can provide local shape information, including contact location on the finger, surface normals, principal curvatures and their direction. From this information, global object properties such as size, location and orientation are inferred. Fearing (1990, p. 236) notes that "the reorientation sub-system would command finger force, stiffness and position. High speed tactile or force sensing can monitor the grasping operation for unexpected forces, contact slip, and loss of contact. The reorientation planner may also continuously monitor object position during reorientation, and develop error recovery strategies if unexpected object loads are encountered". He notes that there are complicated compliance, friction, rolling and slipping effects that can occur at finger-object interfaces.

Rather than relying on sensors, Mason (1985) discussed how humans take advantage of <u>task mechanics</u>. In effect, control places us in the ballpark of the desired locations, forces, torques, motions; then, we use the intrinsic mechanics of the task environment as a funnel to eliminate uncertainties about the locations and shapes of objects (like funneling sand, where the funnel reduces uncertainty in the location of a grain of sand). For example, there is uncertainty in using pad opposition to grasp a pencil resting on a table; i.e., what will happen if one finger contacts the pencil before the other? Instead of trying to make contact exactly, it is possible to use controlled slip. The pencil is grasped between two fingerpads, applying a force in a direction nonorthogonal to the long axis of the pencil. One finger applies a torque, rotating the pencil into stable grasp. Absolute precision is not needed, since a funnel will eliminate position uncertainty despite variations in the initial location, shape and orientation of the pencil. A funnel uses constraints (usually kinematic ones) to limit the possible end configurations of objects. Using an arm to squeeze a pile of parts into the center of a table gets all the parts into the center, independent of friction; dropping a pen onto a table gets the pen flat on the table.

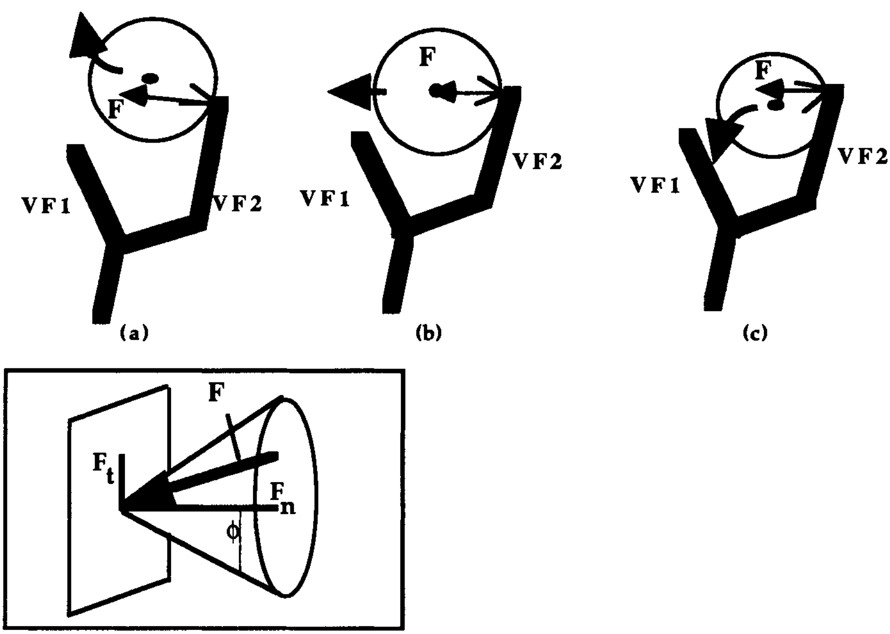

Figure 6.23 Inset shows a geometric interpretation of the cone of friction. The task mechanics of grasping a glass with uncertainty as VF2 makes contact with glass before VF1. The thin arrowed line is the line of pushing, drawn parallel to the motion of the fingers, through the contact point. (a) When it is on the near side of the center of mass, the glass will rotate out of grasp. (b) When it is through the center of mass, the glass will translate towards VF1. (c) When it is to the far side of the center of mass, the glass will rotate into VF1. Example based on Mason (1985).

In impacting an object with fingers, recall the cone of friction[17] (see inset, Figure 6.23). Slip will not occur at the fingers if the direction of the applied force F is within the cone of friction. However, the object will move as a pushing force is applied, and the question to determine is what kind of motion will occur ; e.g., will the pencil rotate clockwise or counterclockwise? Assuming Coulomb friction (recall equation 13), planar motions are either translations or rotations about some instantaneouly motionless point[18]. Mason (1985) constructed an algorithm as a way to predict the direction of rotation in spite of the indeterminancies of the problem. The sense of rotation can be predicted from knowing the limits of the cone of friction R_r and R_l and the direction of the velocity of the pusher F. These three vectors 'vote' on a clockwise or counterclockwise rotation, depending on their relationships to the center of mass. If R_r and R_l (irregardless of F) are to the left or right of the center of mass, the object will rotate clockwise or counterclockwise, respectively. If R_r and R_l disagree (i.e., the center of mass lies within the cone of friction), then the sense of the rotation is based on F.

Suppose, for example, as seen in Figure 6.23, a right hand is picking up a glass in pad opposition and suppose that VF2 makes contact with the glass before VF1. Will the glass rotate into the grasp or out of the grasp? The cone of friction is drawn about a normal to the surface. Assuming that the center of mass of the glass is at the center of the glass, then the center of mass will be within the cone of friction no matter where the glass is touched by VF1. The sense of rotation will depend on the direction at which the finger is moving at contact F. The glass will rotate out of the grasp (Figure 6.23a) if this direction is to the near side of the center of mass. If, instead, it is to the far side (Figure 6.23c), the glass will rotate into VF1. If, however, it is through the center of mass, the glass will not rotate, and translate instead, moving towards VF1.

An interesting analytic example of manipulation is seen in baton twirling. Fearing (1986) showed how a third finger can be used to twirl the pencil like a baton, in relocating the fingers in a dynamic, serial tripod configuration using finger contacts modelled as point contacts with friction. Forces applied within the cone of friction will

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[17] See section 6.3.3 and Figure 6.14.

[18] During translation, a system of frictional forces reduces to a single force through a point whose position is independent of the direction and velocity of motion and whose direction is opposite to the direction of motion (no analagous reduction occurs for rotation).

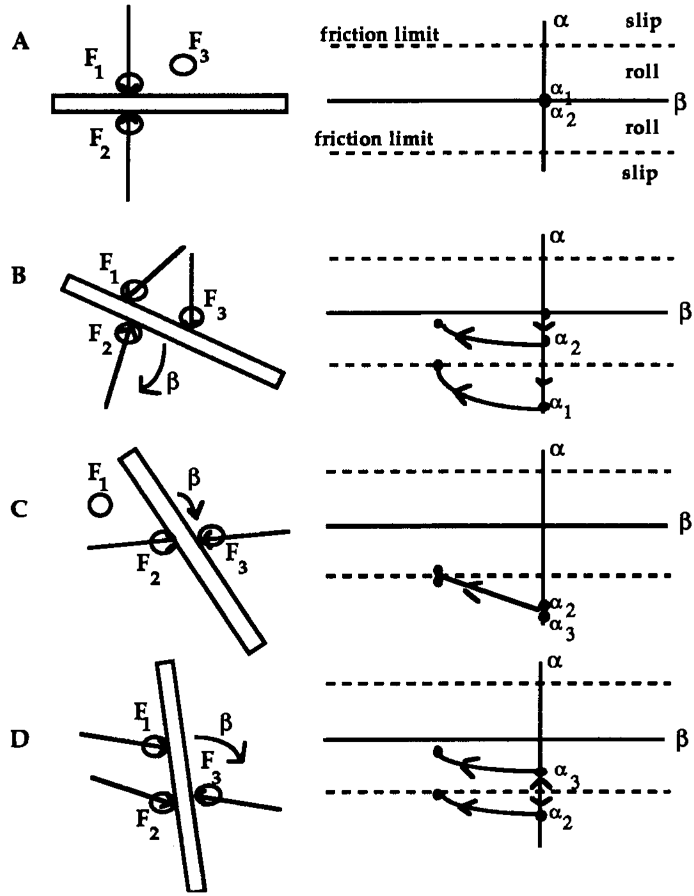

Figure 6.24 'Baton twirling' manipulation by regrasping using three fingers. Sequence of finger placement is seen on left, and force angles α_i are plotted over the rotation angle β, caused by the disturbance. A. Baton is held in stable grasp using finger F_1 and finger F_2. Both fingers are perpendicular to the surfaces, so α_1 and α_2 are zero. B. Finger F_3 applies a disturbance force, causing force angles α_1 and α_2 increase. Angle α_2, the fixed point of contact, is still within friction cone but α_1 goes outside friction limit. Baton begins to rotate around F_2, and finger F_1 slides. C. Finger F_1 is removed, and a restoring force brings α_1 and α_2 back to the stable zone. D. Finger F_1 applies a disturbance force and rotation occurs around F_3, the fixed point of contact. Finger F_2 slides to the stable zone (from Fearing, 1986; adapted by permission).

cause rotations into a stable grasp if the forces are not colinear, creating a stable band inside the friction limits (see Figure 6.24). Slipping will occur if the force is outside the cone of friction. Each force makes an angle α_i with a normal to the surface. A displacement that moves the force angles outside the stable region will generate a restoring force that tends to bring both angles back within the stable limits. As seen in Figure 6.24a, two fingers initially grasp the object in a stable grasp. Since the applied force angles α_i are parallel to the surface normal, α_1 and α_2 are zero. In Figure 6.24b, a third finger applies a force to the object, causing a disturbance. The disturbance force is considered to act through a fixed point, here, the second finger. The forces are no longer perpendicular to the surface, and α_1 and α_2 increase. The baton rotates about second finger, since α_2 is still within the friction cone. The first finger is removed, and the object rotates into a new stable configuration, grasped between the second and third fingers. Applying finger 1 again, in Figure 6.24d, will cause a disturbance, and the process will continue, as long as rotation without slip about the fixed finger is ensured.

6.7 Releasing an Opposition Space

After transporting or manipulating an object, the object is either dropped, or transferred to some other supporting surface, like a table top, or another hand. After using an opposition space, the object is released by extending the fingers and withdrawing the arm.

With respect to letting go of the object, an interesting observation was made by Wing and Fraser (1983) in their examination of hand posturing during the preshaping and releasing phases. They examined a woman with congenital absence of the left forearm and hand; she had an artificial hand of a design where a harness over the contralateral shoulder is used to tension the hand against a strong spring that keeps the fingers (as one unit) and thumb normally closed together. Shoulder movement provided information about the state of opening of the hand. In comparing the natural hand of the young woman with her artificial hand, they had earlier observed that maximum aperture during the reach was paralleled for both hands (Wing & Fraser, 1983). In comparing maximum pertures prior to grasping and after releasing, they found that the left, prosthetic hand had a larger aperture after release than prior to grasp; in contrast, the right, natural hand had a larger aperture prior to grasp than during release. They suggest that the main reason for this is that the artificial hand does not have tactile input from the fingertips during grasping, thus contributing to an indeterminate sense of their position and loading. Given Johansson & Westling's reports on the role of FAII afferents signalling contact with the table at release, this is likely so. The dowel was unstable and could easily be knocked over. Thus, the individual opened the hand wider on release, relying more on visual guidance in withdrawing the prosthetic hand than the natural hand.

6.8 Summary of Using an Opposition Space

We defined prehension as the application of functionally effective forces to an object for a task, given numerous constraints. Figure 6.25 shows the sensorimotor features of the hand considered in this chapter, along with relevant task and object properties for establishing and maintaining stable grasp, and moving between points of stability in manipulation. A distinction was made between active touch and active manipulation; sensory information is gathered for both. Both the process and the product of force generation were examined during compliant motion phases, noting how the system responds to various task demands and levels of perturbations, from microslips to external interference.

The hand was considered as both an input and an output device. We discussed how the hand gathers sensory information about the object, the state of interaction with the object for a task, or the task outcomes, through proprioceptors (skin, muscle and joint receptors) and exteroceptors (skin receptors and vision). In this regard, skin is a critical organ providing housing for muscles, mechanoreceptors and eccrine sweat glands, essential for establishing stable grasp. Palmar creases, or flexure lines, reflect axes of movement. Some characteristics of skin relevant to force generation and adhesion include: characteristics of epidermis, dermis and their interface; papillary ridges; eccrine glands; sensory receptors; and their innervation. Papillary ridges extend over grasping surfaces that comply with the environment, as evidenced by human hands, gorilla knuckle pads and prehensile monkey tails. They act like ridges on automobile tires, to increase grip and facilitate weight bearing by increasing surface area. The concentric arrangement of the ridges makes some asperities always perpendicular to shearing forces. Moberg (1962) noted that a patient with impaired sensibility in the median nerve region has difficulties with manipulations using pad opposition, like buttoning and unbuttoning; in contrast, patients with impaired eccrine functions (dry or very wet hands) more often have difficulties with tools using palm opposition - the subsequent loss of

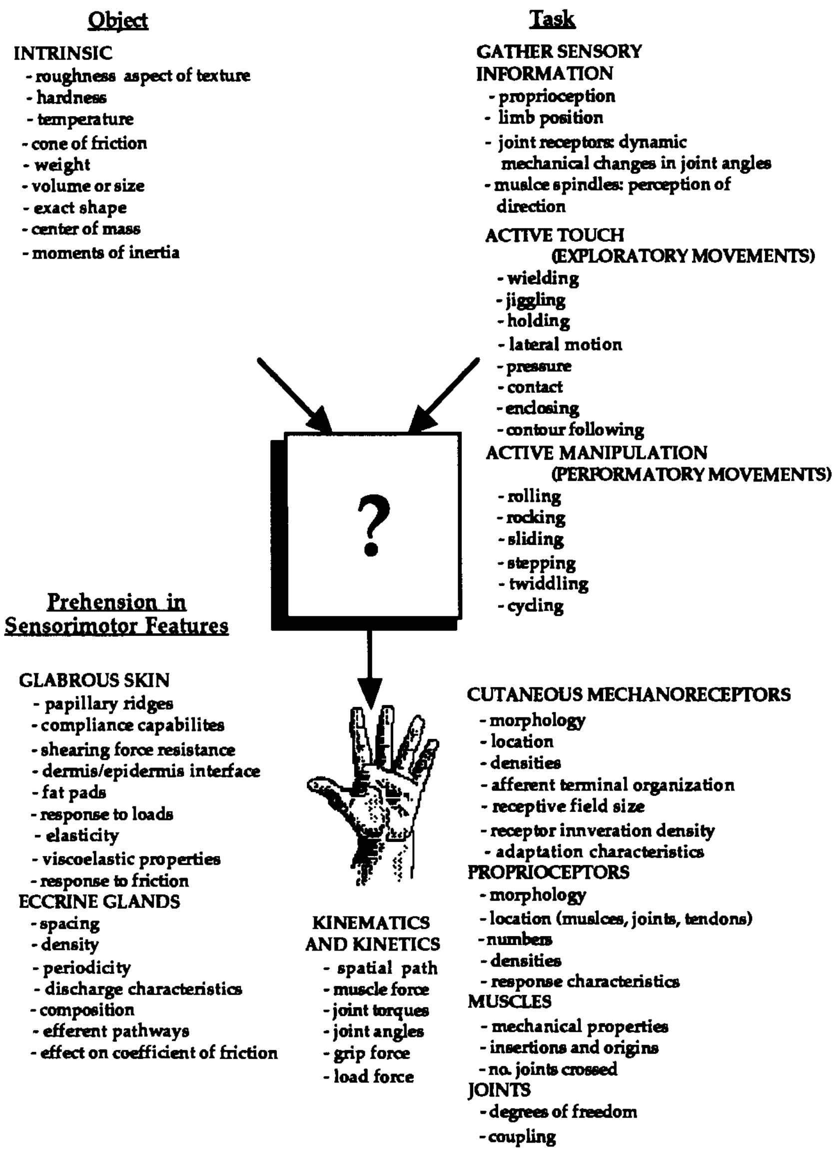

Figure 6.25. Black box revisited during contact, while using an opposition space.

friction leads to reports that an axe or hammer is likely to fly out of the hand.

Object characteristics relevant for stable grasping may be assessed with varying degrees of accuracy through either vision or haptics. Different sensory modalities, tactile or visual, seem to have access to different object properties. Many object properties interact in our perception, thus setting up anticipated values (e.g., large objects are perceived to be heavy). With respect to task requirements, a distinction has been made between exploratory movements, with a goal to extract object property information, and performatory movements, where sensory information is important to assess the state of interaction with the object in transportation or manipulation. These two classes of movements have different temporal frequency domains and different modes of sensory control.

Physical characteristics of the object's structure determine the nature of the interaction in stable grasping: the object and the hand surfaces together determine the coefficient of friction. A formal analytic description of the mechanics of stable grasp was provided. The hand generates appropriate forces along the opposition vector(s) for grasping and manipulative stability, using the muscles (somatically innervated sensorimotor system) in parallel with the eccrine sweat glands (autonomically innervated sudomotor system), given the inherent 'passive' structural characteristics of the hand.

A crucial variable for control during contact is that the system being controlled is first the hand, then the hand plus object. The process of acquiring objects into stable grasp can be broken down further into subphases. 'Triggering' of these subphases seems critically dependent on making and breaking contacts with the environment (contact between the hand and object, contact between the hand plus object with supporting surfaces).

We examined briefly, from human studies and robotics, stable grasping for transporting objects and the more complex problem of object manipulation, where an object is in 'controlled slip'. In considering object manipulation, we noted that while Elliott and Connolly (1984) provided symbolic descriptions of some manipulations, the coordinate frame for defining opposition space in Chapter 2 was extended to describe such manipulations.

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Chapter 7. Summary of Opposition Space Phases

"All my life's a circle".

A hammer sits on the table in front of you. You reach out, pick it up, place the hammer on shelf, and continue with your daily tasks, grasping and manipulating objects frequently. What was involved in this two second task?

You probably turned your eyes and head to foveate the object, though this was not necessary. Using vision, you perceived task-relevant object characteristics, such as its orientation on the table, the surface texture, length and width of the handle and the hammerhead. Using proprioception and vision, you perceived your own body configuration and its relation to the hammer. You 'saw' an opposition vector on the object, a key driving variable in planning and control that allowed you to envision an appropriate place to grasp the hammer, given the task, the assumed cone of friction, weight, center and distribution of mass. Movement began and, as your arm reached out, anticipatory shaping of the fingers occurred; again, appropriate for the task. Then, your fingers began to enclose around the hammer. After initial contact, your hand captured the hammer and established a stable grasp by complying with the hammer (and likely the table as well), generating the necessary, functionally effective forces to achieve the goal of the task, i.e., grasping the hammer for placement. Creating a stable grasp meant taking into account the complex interactions between the hammer's and your hand's surfaces. Without it, the object would slip and even fall out of your hand. Your muscles contracted to supply the necessary forces in the finger flexors with cocontraction in the extensors, which caused torques at each joint in the hand. Your skin deformed, and sensory signals from your cutaneous and proprioceptive receptors were sent back to your spinal cord and brain for further motor actions. Your hand had to resist small external perturbations and generate restoring torques and forces to ensure manipulative stability. While maintaining that stable grasp, you lifted the hammer, transported it to a location above the shelf, and then placed it on the shelf. As you let go of the hammer, your eyes and head turned to focus on the next object to be grasped.

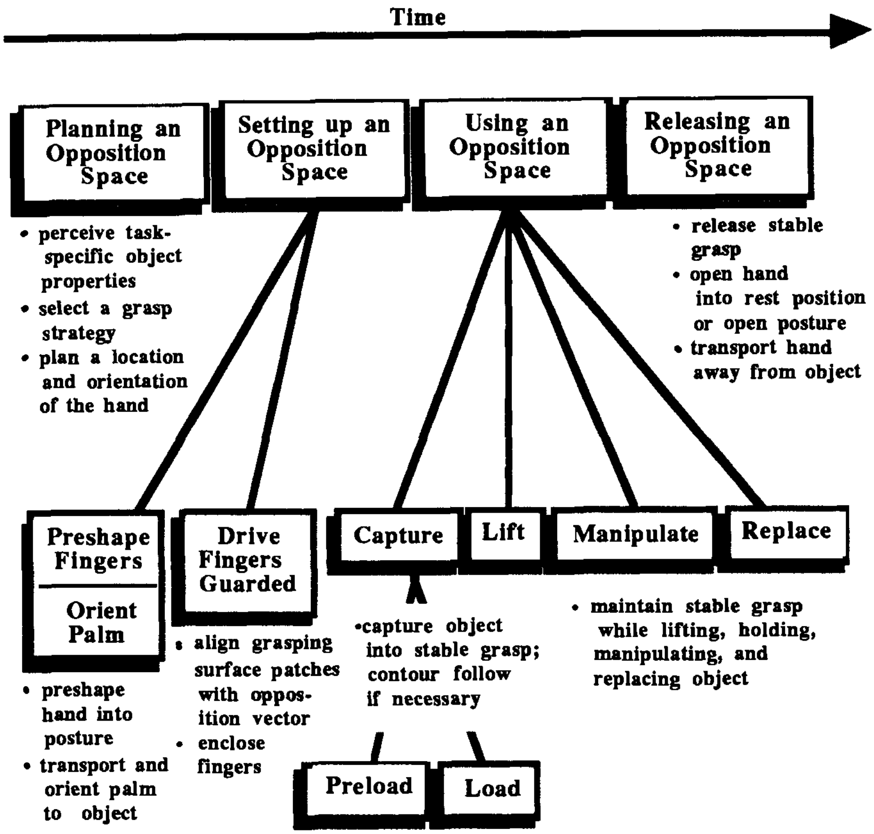

Figure 7.1 Phases in Opposition Space Analysis of Prehension. Prior to grasping, there is a planning phase for choosing an opposition space, based on motivations and task context. The choice of an opposition space includes: the opposition vector, the opposition type(s), virtual fingers, and the parameterization for these. Setting up an opposition space requires activity of the proximal and distal muscles for locating and orienting the palm, and distal muscles for posturing the fingers. After peak aperture, the enclosing is a guarded motion anticipating contact. This bridges the free, unrestrained motion with the compliant motion. Using an opposition space involves the application and modulation of functionally effective forces to stably grasp and release the object. With a magnet reaction, the gripping forces decrease and the hand releases opposition space, by letting go. For setting up and releasing an opposition space, only the arm and hand are controlled; in contrast, when using an opposition space, the object also becomes a part of the controlled system.

In Chapters 3-6, we considered phases that seem to be distinct in prehension. Planning, reaching, grasping, manipulating, and releasing the object all entail different activities. A conceptual model is presented in Figure 7.1 as a plan for effecting a prehensile movement. Such a task plan ties together the serialization of multiple sub-tasks, such as transporting the hand to the correct location and orientation and shaping the hand into a posture suitable for the object and task. Across the top shows a rather high level description of the task plan for prehension, unfolded over time. The task plan includes the following phases:

1. Planning an Opposition Space,
2. Setting Up an Opposition Space,
3. Using an Opposition Space, and
4. Releasing an Opposition Space.

Within each phase, computational processes and subphases occur, as detailed below.

In evaluating prehensile behavior, experimenters have adopted one of two main paradigms: focusing on the movement prior to contact (paradigms discussed in Chapter 5), or focusing on the forces applied during contact (paradigms discussed in Chapter 6). In Chapter 5, detailed examination of the limb kinematics, spatial paths, and hand configuration revealed organization and control while setting up an opposition. In Chapter 6, detailed analyses of forces, EMG, sensorimotor features and analytic measures revealed control while using an opposition space. For lifting an object, Figure 7.2 shows an integrated, synchronized view of the kinematics and grasping forces from movement onset through acquisition into stable grasp, lifting, replacing and releasing an object. Shown is a single trial in which a human subject reached for a 155 g dowel (3.8 cm diameter, 11.5 cm long) placed 20 cm in front of the midline sagittal starting point, grasped it with pad opposition between thumb and index finger pads, lifted it to match the height of a 4 cm block, replaced it on the contact plate and returned to the starting posture. The entire movement sequence had a duration of 2.4 s. <u>Free motion</u> occurs from movement onset to peak aperture between the thumb and index finger. <u>Guarded motion</u> occurs as the fingers enclose, anticipating contact with the object. <u>Compliant motion</u> occurs from object contact until the object is let-go. There is another period of compliant motion as the object is replaced on the table until release. After letting go of the object, the hand is in free motion. We now consider what is happening during these phases in an Opposition Space analysis of prehension.

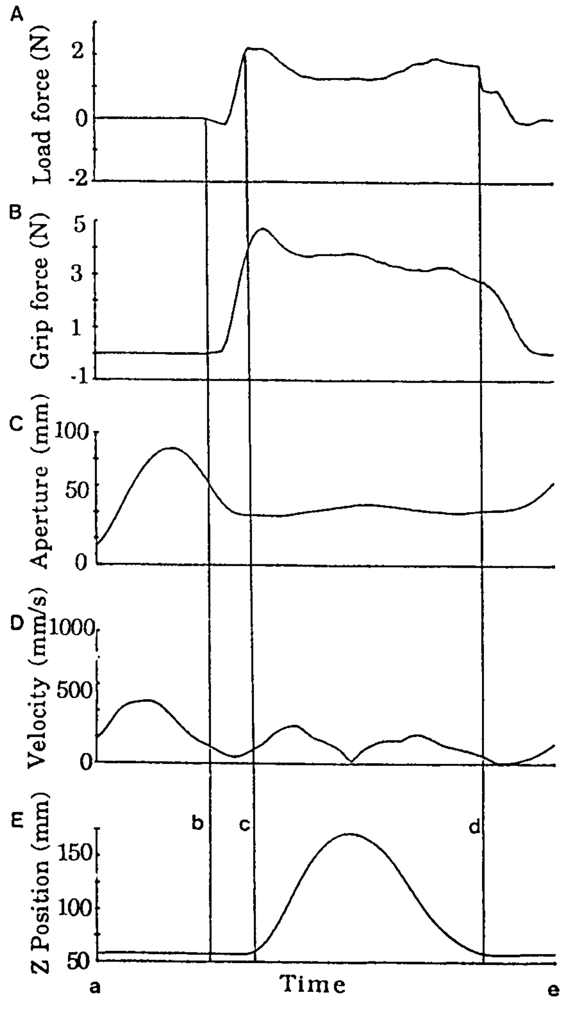

Figure 7.2 Synchronized force and kinematic profiles for a subject Setting Up an Opposition Space and Using an Opposition Space. The task required the subject to reach and grasp a 3.8 cm diameter dowel, lift it 4 cm high, replace the dowel, and release it. A. Load force, B. Grip force, C. Aperture between thumb and index finger, D. Wrist velocity and E. Vertical dowel position. Lower case letters represent the times of: a. Hand lift, b. Dowel contact, c. Dowel lift, d. Dowel replace, and e. Let-go of the dowel. See text for details (Adapted from Weir, 1991, by permission).

7.1 Planning an Opposition Space

In order to perform the simple task of lifting an object such as a hammer, preparatory processes related to the organization and planning of the upcoming movement occur in the CNS, coordinating such a highly complex activity. In our model, this first step in the task plan involves selecting an opposition space useful for the task. This involves three aspects:

1) perceiving task-specific object properties,
2) selecting a grasp strategy, and
3) planning a hand location and orientation.

The choice of an opposition space depends on information perceived about an object, including extrinsic and intrinsic properties. The particular properties perceived are task-related. For example, color is not particularly useful for grasping, unless we wish to select objects only of a particular color, i.e., other than helping to distinguish color as a feature of the object. Experimental evidence suggests that intrinsic object properties, such as size and shape and surface spatial density, and extrinsic object properties, such as object location and orientation, are perceived prior to movement. Weight is estimated, based on size/weight relationships. The particular properties are also perceived in a hand related manner. Surfaces discounted for grasping include inaccessible surfaces, surfaces too wide for the hand's span, and surfaces too narrow for the hand's width. Part of the choosing of an opposition space entails seeing an opposition vector which has a hand-sized magnitude between two hand-sized surfaces that will satisfy the required degrees of freedom of the task. Figure 7.3 summarizes this notion, showing the opposition vector and its properties. The opposition vector has an orientation with respect to an approach vector.

The choice of an opposition space also depends on previous knowledge about the behavior of objects that our brains have collected over time (phylogenetically and ontogenetically), and our ability to predict and anticipate task-specific prehensile occurrences. For example, the thumb and index finger do not precisely have to grasp the object at the same time. One can anticipate how to 'push' the object into the grasp. This knowledge includes anticipation of object rotations and translations in relationship to where fingers are placed relative to the object's center of mass. In addition, knowledge about the cone of friction is necessary for anticipating where to grasp and how to approach the object. We know that gravity will make objects drop. These all contribute to the selection of an opposition vector. Torques caused by locating the opposition vector to the side of the center of mass are anticipated in the frame of reference created by the opposition vector.

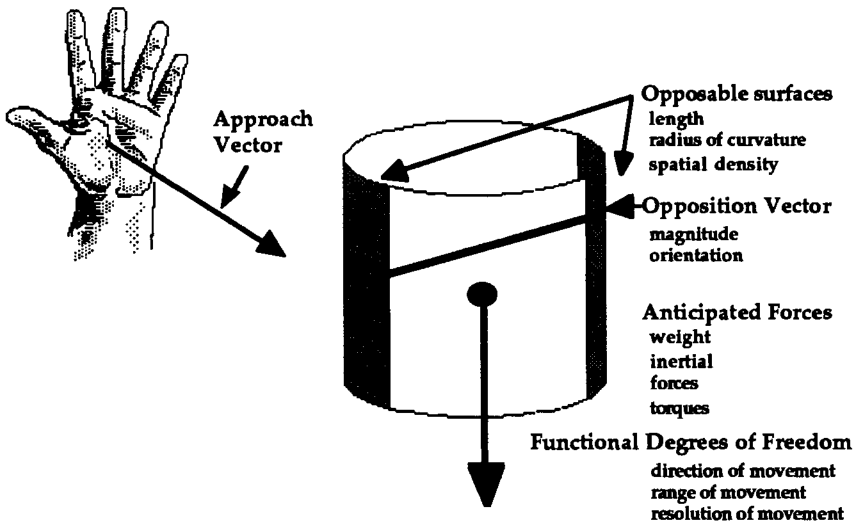

Figure 7.3. Opposition vector seen in the object, perceived with a magnitude between two opposable surfaces and an orientation relative to an approach vector from the palm of the hand.

Secondly, the choice of an opposition space depends on choosing a grasp strategy. This is quite dependent on a person's anatomy, emotional state, intentions, fatigue level, motivations, sociocultural milieu, and so on. The term 'grasp strategy' refers to selecting appropriate opposition types, mapping virtual fingers onto real anatomical fingers, and determining opposition space parameters that will ultimately define the shape of the posture. A grasp strategy is chosen in accordance with the task, so that functionally effective forces of a given direction and magnitude may be applied. The key, though, is that the choice of the opposition vector must satisfy the constraints imposed by the object, task, and hand. As Napier (1956) pointed out, the precision and power capabilities of the human hand can match the requirements of the task. Computational models have demonstrated possible ways to map object and task characteristics to hand postures, using expert systems and neural networks. Expert systems make explicit the rules of these mappings; neural networks can learn the rules. Yet, none of these are performing the mapping the other way; i.e., how do the constraints of hand anatomy (level of fatigue, motivations, etc.) drive the choice of the opposition vector?

Thirdly, a location and orientation in space for the hand to go to must be planned. Planning a hand location and orientation will depend on the grasp strategy chosen. Such a decision can be based on retinal information or on knowledge about the hand. It has been shown how wrist orientation is affected by task constraints. But this is the same issue as raised above. Constraints of the anatomy and other biological and motivational factors affect the perceived opposition vector, and thus the choice of the opposition space of the hand.

How this plan is constructed in the brain is open to discussion. In Chapters 3 and 4, task plans from a variety of fields were examined, showing possible mechanisms for programming phases, for integrating feedforward and feedback controllers, and for including contingencies for error. Some models suggested distributed control, others hierarchical control. Other models suggested how plans could be mapped out across regions of cortical and sub-cortical areas in the CNS. Neural recordings have amply demonstrated the CNS is computing something; what it is computing is unknown. Importantly, planning takes time, and reaction time studies have demonstrated that the more complex the movement, the longer the reaction time. Of course, subsequent movements can be planned during initial movements.

From the experiments and computational models put forth in Chapters 3-4, the underlying hypotheses are made explicit for the reader's further evaluation and research:

1. A task plan is built in terms of sensory consequences (Abbs and Cole, 1987).
2. Motor equivalence suggests task planning does not occur at the muscle level.
3. A minimal amount of time is needed for planning. More time is needed for a more complicated serial task (Henry & Rogers, 1960).
4. Kuperstein (1988) built associations of maps between the eye position and arm configuration. This suggests that a person must look at where he/she wants the arm to go before movement occurs.

5. Selection of a wrist position is done for comfort in the task, but if two tasks are involved, sometimes the comfort is for the second task (Rosenbaum et al., 1990).
6. Retinal information can be used for perceiving object properties for planning a grasping strategy (Klatzky, McCloskey, Doherty, Pellegrino & Smith 1987; Sivak & MacKenzie, 1992).
7. Planning is done in terms of 'ballpark' planning (Arbib et al., 1985; Greene, 1972; Iberall, 1987a; Iberall & MacKenzie, 1988).
8. Object properties are perceived in hand-sized dimensions (Newell et al., 1989).
9. Weight can be estimated from vision.
10. Multiple solutions exist for grasping objects for a given task.
11. The opposition vector is seen in the object and creates a task coordinate frame.
12. The approach vector is in a palm-centered coordinate frame.
13. Force generation is computed in a palm-centered coodinate frame, given the opposition vector.
14. During planning, vision is a dominant source of sensory information.

7.2 Setting Up an Opposition Space

Given the perceived opposition vector, once hand locations and postures are chosen, commands must be generated to set up the opposition space and transport it towards the object. Figure 7.4 (introduced earlier as Figure 5.32) shows a palm-focused model of Setting Up an Opposition Space, and includes a Preshape Schema, and Orient Palm Schema, and a Drive Fingers Guarded Schema. In this view, computations for finger control are in a palm-based coordinate frame. Noting the interwoven action of wrist, forearm, elbow, and shoulder muscles, we suggest that the palm is the likely interface between the transport and shaping of the hand.

The relationship between the transport and grasping components appears to be functionally specific to the high level goal of the task. Research has suggested a coupling between these two components, indicating that the way the arm behaves alone (as in pointing movements) is different from the way the arm works when the hand is involved (as in reaching and grasping movements). The way in which the transport and shaping of the hand are coordinated is still an open question. Some researchers show temporal invariance, and others disagree, arguing that although the two components are not time-locked, they are spatially and functionally coupled. The Drive Fingers Guarded Schema in Figure 7.4 is controlling the final positioning of the grasping surface patches of the hand, through proximal and distal muscles. That is, the model suggests that there are not separable transport and grasp components in the final approach to the object. All control is directed to alignment and the placement of the grasping surface patches on the hand with respect to the palm and object.

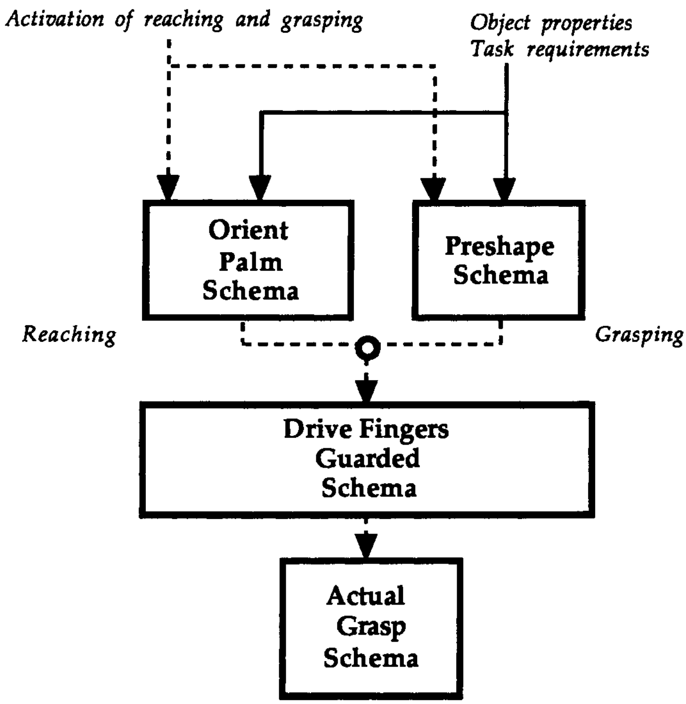

Figure 7.4 Palm-focused model of Setting Up Opposition Space for prehension. During activation of the Orient Palm Schema, reaching movements orient the palm and position it close to the object. In parallel, the Preshape Schema shapes the fingers into a posture suitable for that palm alignment. When preshaped, positioned, and oriented, the Drive Fingers Guarded Schema is activated in order to drive the arm, wrist, and hand in a direction to make contact with the object. Since it is a guarded move, contact with the object will stop the schema, and activate the Actual Grasp Schema.

Fitts' Law, one of the few lawful relationships in motor control, demonstrates a speed-accurarcy tradeoff in many movements. Asymmetric velocity profiles point to the possibility of a two-phase controller for complex movements where interaction with the environment is required. The environmentally-defined goal seems to suggest that a precision effect might be in play in these situations. This precision effect shows up in the second part of the movement where sensory information is needed for changing from an unrestrained movement to a guarded movement. As seen in Figure 7.4, preshaping the fingers and orienting the palm are concurrent activities, to get the hand configuration 'in the ballpark' of the object during the first phase.

During the preshape, from movement onset to peak aperture, the hand moves in an unrestrained way. The preshaping of the hand into a suitable posture for the task is an inherently unique event. It sets up the opposition space, with the posture chosen reflecting perceived object properties, such as size and shape, and also task properties. The force production muscles are stretched, preparing to be used. In order to accomplish this setting up, sensory information is needed -- proprioceptive usually, but if it is not available through some sort of neural dysfunction, then vision can be used. In situations where sensory information is reduced (e.g., blind conditions, fast movements), the hand opens wider. If planning is occurring in terms of sensory consequences, then during preshaping, there would be no anticipated tactile feedback. Accidental contact with the object is avoided. In terms of a controller, if the free motion is ballistic, then contact is of course ignored.

As the fingers are enclosing, a transition is occurring between the previously unrestrained movements of preshaping and the upcoming compliant motions to be made during contact with the object. During this transition phase, the hand is performing a guarded motion, trying to establish tactile contact. Sensory information is sought by the Drive Fingers Guarded Schema, comparing the anticipated tactile feedback to the current haptic information. The chosen pads (for pad opposition, or more generally, grasping surface patches for all oppositions) are being brought into a specific contact with the object. Research has shown that the CNS knows the direction that the pads are pointing. The arm is subservient to the hand, helping in the guarded move to establish contact. The force-generating muscles are active to 'drive the fingers' around the object. Central vision can compare the location of some part of the hand with the object, since both are within a small visual field. The controller can use the cone of friction as a ballpark to be within; i.e., as long as the applied force of the fingers is directed within the cone of friction, the object will not slide relative to the fingers. The fingers do not have to make contact simultaneously, since knowledge of task mechanics will have ensured that being in the ballpark of the chosen opposition vector will rotate or push the object into the grasp, instead of out of the grasp.

Two major goals seem to be at work, which in their own way influence both the arm and the hand. Firstly, perception of the location of the object influences movement parameters; uncertainty in object location dictates slowing down in the vicinity of the object, particularly if the objective is not to bowl it over or crush it. This affects both the transport and orientation of the palm (change in velocity profile, systematic changes in palm orientation) and the grasping component (open hand wider before contact is anticipated). Secondly, perception of force-related object properties (e.g., weight, surface texture, surface sizes) and goals for task performance (e.g., direction and type of motions to impart, forces to apply) show systematic kinematic and kinetic effects appropriate for the upcoming grasping demands. The hand must be postured to optimize the force generating muscles for the task.

Different models of control have been suggested. The level of these commands could initially be in hand space, thus a trajectory would be generated involving hand positions and speeds along a path in a body or world coordinate frame. The alternative is to do this in joint space, so that paths are specified in an intrinsic frame of reference, such as shoulder and elbow joint angles. The actual generation of a motor command would involve translating these commands (or even high level goals) into the space within which the actual movement is being driven. Models have suggested how a motor command could occur at the joint angle level, joint torque level, and muscle level. Experimental evidence shows the computation of a population vector for direction of movement. If the control variables are kinematic ones, this is an inverse kinematic problem. If the control variables are dynamic ones, such as joint torques over time, this is an inverse dynamic problem. Inverse problems are underconstrained in that there are non-unique solutions, especially in a system as complicated as the human arm, involving 11 degrees of freedom, over 30 muscles, thousands of muscle fibers, multi-joint muscles, and coupled degrees of freedom. For limiting the computation towards selecting a unique solution, cost functions and/or constraint satisfaction networks have been suggested that minimize some measure, such as potential energy, or movement time, or changes in accelerations or torques. Treating muscles as tunable springs is another possible method of control, suggesting that the CNS need only set a new equilibrium point for the muscles, thus avoiding the need for a more active controller. Of course, the CNS never seems to have a unique solution, evidenced by the issue of motor equivalence and also of the exhibited variability. One possibility for how computations are performed is that the CNS uses linear approximations of the exact nonlinear relation between limb segment angles and target locations.

The CNS may be trying to get some parameters into the 'right ballpark' which can then be fine tuned. This could be the threshold of motoneuron recruitment as a parameter that will cause movement once it is set. The setting of such a parameter, in terms of prehension, must be related to high level task goals. It was shown that kinematic parameters can be used for satisfying high level goals. The palm is placed into a ballpark of its final orientation and location, and an opposition space controller puts virtual finger parameters into the right ballpark of their goal configuration. A desired posture and position are computed from estimated object location, orientation, and size, and a feedforward controller gets the hand and arm into the right ballpark during the first phase of the movement. Feedback mechanisms then overcome errors in perception during the second phase of the movement.

Importantly, during the setting up of an opposition space, movements are concerned with directions and distances. Polar coordinate frames, whether centered in the head, sternum, shoulder, wrist, or palm, set up a convenient way to view this setting up process. Direction and distance appear to be parallel dimensions and the CNS seems capable of computing directions quite accurately. The opposition vector determines the directional planning for the hand configuration, both for the hand with respect to the body midline, and the grasping surface patches of the fingers with respect to the palm.

From the experiments and computational models put forth in Chapter 5, the underlying hypotheses are made explicit for the reader's further evaluation and research:

1. Set up occurs in parallel, and therefore no extra time is needed to set up a more complicated grasp.
2. There is a functional relationship between preshaping and transporting (Jeannerod, 1984).
3. Pointing is different from reaching and grasping (Marteniuk et al., 1987).

4. Temporal invariances can occur between transport and grasp (Jeannerod, 1984).
5. Spatial invariances can occur between transport and grasp (Wing & Fraser, 1983; Wing, Turton & Fraser, 1986).
6. The index of difficulty of the task affects the transport component (Marteniuk et al., 1987).
7. Precision effects occur in deceleration (Marteniuk et al., 1987).
8. Preshaping is different from enclosing (Jeannerod, 1984; Marteniuk et al., 1987).
9. Location of the object influences movement parameters (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991).
10. Force-related object properties affect the transport component.
11. Task goals affect the transport component (Marteniuk et al., 1987).
12. The posture chosen reflects perceived object properties and task properties (Arbib et al., 1985; Jeannerod, 1981, 1984; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990).
13. Contact is avoided during preshaping.
14. The CNS transforms information between coordinate frames (Georgopoulos et al., 1988).
15. A population vector for movement direction is computed in motor cortex (Georgopoulos et al., 1988; Kettner et al., 1988, Schwartz et al., 1988).
16. Muscles are tunable springs (Feldman, 1986).
17. Preshaping is getting fingers into right ballpark.
18. The first phase of orienting the palm is getting the hand into the right ballpark of location and palm orientation.
19. An arm trajectory is computed in body coordinates from goal location (Massone & Bizzi, 1989).
20. The CNS can compute inverse kinematic computations, generating joint angles from goal locations, using an adaptive constraint network (Jordan, 1988).
21. The CNS maintains internal models of dynamics and of inverse dynamics for replacing feedback control with feedforward control as movement is learned (Kawato et al., 1987).
22. Hand movement is a two-phase movement, and first phase is feedforward, while second phase is feedback.
23. Preshape movement is occurring in a feedforward sense.
24. Orient palm is feedforward.
25. Sensory information is needed for preshaping (Jeannerod, 1986).
26. Peripheral vision is used for arm movements (Sivak, 1989).

27. Central vision is used to preshape the hand (Sivak & MacKenzie, 1990).
28. Proprioception is needed to orient the palm and preshape the hand.
29. The parietal lobe is needed to orient the palm and preshape the hand (Jeannerod, 1986).
30. For grasping, the arm is subservient to the hand (Marteniuk et al., 1990).
31. Enclosing in pad opposition aligns the pads (if possible) (Cole and Abbs, 1987).
32. The force-generating muscles become active at the start of the Enclose Phase (Smith et al., 1983).
33. The coordinate frame for transporting the hand to the object is polar-centered, with the origin in the sternum.
34. The coordinate frame for finger movements is polar-centered, with the origin in the palm.

7.3 Using an Opposition Space

Once the opposition space is set up, it can then be used. At contact, stable grasp or stable manipulation is effected, by correctly positioning the opposition space around the object. This occurs during the Capture Phase, which involves compliant motion against the object. The Capture Phase is triggered by contact with the object. Contour following can possibly occur. During the Preload subphase, the grip force, or normal component of the active force, increases. Then, during the Load subphase, both the grip force and the load force (tangential or gravitational component) increase in parallel, with the load force counteracting the object's weight. If the active forces are of insufficient magnitude, microslips from the cutaneous receptors will signal motor adjustments to be made. This pressure must be maintained during the lifting, holding, manipulating, and replacing of the object.

During these compliant motion phases, the opposition vector specifies directions and magnitudes of forces to be applied. As in the Setting Up of Opposition Space, direction and magnitude of forces may be parallel dimensions as well. A complex interplay between kinesthetic, tactile and motor processes allows the hand to apply forces and obtain required sensory information for the interaction.

The hand, as both an input and output device, has a somewhat unique capability in that it can grasp to feel and feel to grasp (see Figure 7.5, first introduced as Figure 6.5). Active touch allows object

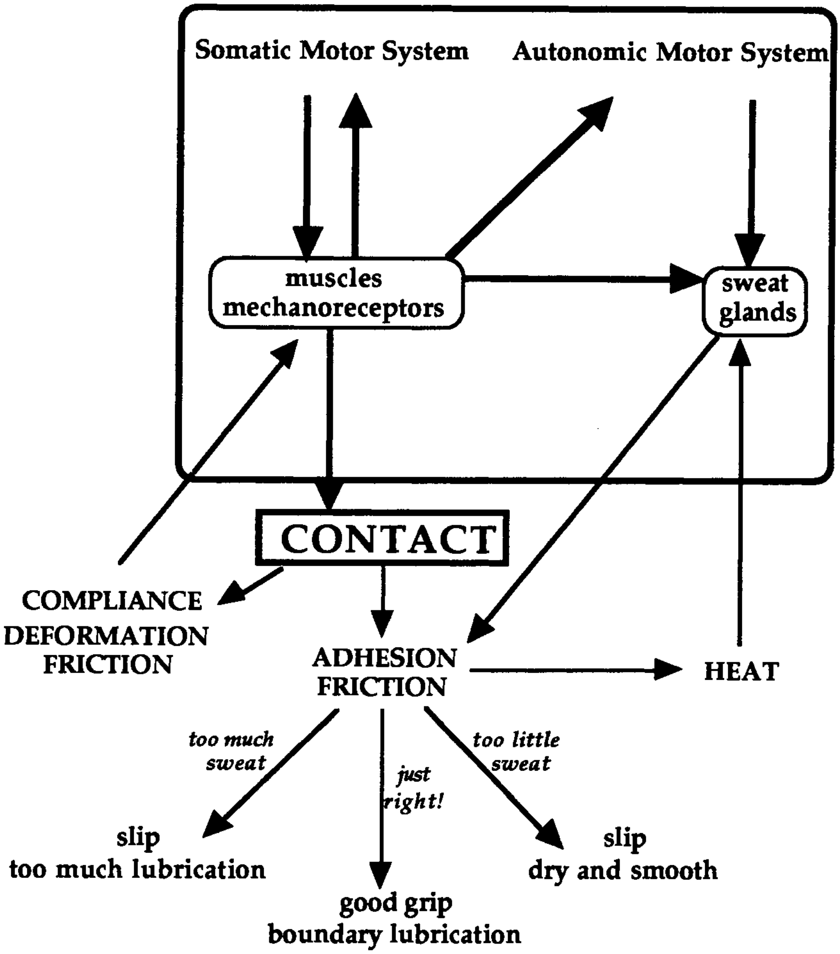

Figure 7.5 In using an opposition space, the hand generates appropriate forces along the opposition vector(s) for grasping and manipulative stability, using the muscles (somatically innervated sensorimotor system) in parallel with the eccrine sweat glands (autonomically innervated sudomotor system). There is a complex interplay between the muscles, mechanoreceptors (joint, muscle, skin), and sweat glands (likely vasodilators also). Healthy sweating provides boundary lubrication of the palmar surface of the hand, adhesion, and good grip. With contact, the skin is deformed, activating mechanoreceptors, and creating heat through friction. Both of these may lead to secretions by the sweat glands.

characteristics, such as surface texture, hardness, temperature, object size and shape, to be explored. Since the visual system supplied only an approximation of many of these (e.g., spatial density, weight, size, shape), active touch makes available more accurate information for the ensuing phases. When the desired placement of the hand surfaces is achieved, the force-generating muscles begin their second function, that of 'generating the forces' against the object. If holding the object is part of the task, then a stable grasp must be effected. The contacting surfaces of the hand must support the weight of the object. Therefore, the muscles must be set to lengths that generate the necessary forces without undue strain on themselves as well as on the bones, joint capsules, and tendons. Using the frictional components of skin, such as the epidermal ridges, fatty pads and sweat glands, the amount of active force needed can be reduced, as long as the pads are placed correctly.

From the experiments and computational models put forth in Chapter 6, the underlying hypotheses are made explicit for the reader's further evaluation and research:

1. Perturbations can occur during contact. To compute a new opposition space while using an opposition space would take time. To deal with perturbations that fit within constraints of chosen opposition space wouldn't take much extra time (Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991; Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991).
2. During contact, haptic perturbations will be more powerful than visual perturbations.
3. The highest goal in a hierarchy of goals will tune others.
4. If the goal is to place an object on a support surface, and the support surface is moving, this will affect grasp.
6. Knowledge of task mechanics is used to predict the behavior of the object as the hand makes contact and tries to establish a stable grasp (Mason, 1986; Rosenbaum et al., 1990).
7. A stable grasp is not always formed before manipulation begins.
8. There are subphases to using an opposition space (Johansson & Westling, 1984, 1987, 1990).
9. Analogous control processes and organizational principles apply to the fovea of the eye and the pads of the fingers.
10. The cone of friction creates a ballpark for placement of the grasping surface patch of a virtual finger.

11. Contour following is a ballpark of the actual opposition vector, using task mechanics.
12. Controlled slipping is a ballpark (Johansson & Westling, 1984, 1987, 1990).
13. The coordinate frame for finger muscles is palm-centered in using an opposition space.
14. The controller being used is feedback or feedforward.
15. If contact is not made with the object in a certain amount of time, the controller for enclosing the fingers will signal other schemas (Arbib et al., 1985).
16. Decreasing grip and load forces is a transition, anticipating transfer of support to another surface.
17. Perturbations during the decrease in load and grip forces prior to release will cause an increase in these forces, delaying the release.

7.4 Releasing an Opposition Space

Once support for the object has been transferred to another support surface, the opposition space can be released. The hand opens, relaxing usually into the position of rest, or position of function, where the muscles and tendons are in an equilibrium position. The shoulder and arm transport the hand away from the object.

From the experiments and computational models put forth in Chapter 6, the underlying hypotheses are made explicit for the reader's further evaluation and research:

1. The hand drives the arm.
2. There are feedforward anticipatory mechanisms of control.
3. No vision is needed.

7.5 Summary of Opposition Space Phases

Prehension seems to involve a series of phases. 'Triggering' of these phases seems critically dependent on making and breaking contacts with the environment (contact between hand and object, contact between hand plus object and supporting surfaces). Unique to each phase are the motor characteristics, the influences of sensory information, the intent or goal, the context within it is occurring, and the corresponding neural events. The Planning Phase demonstrates much brain activity in anticipation of the movement, drawing on previous knowledge of object/hand interactions. Opposition vector(s) are seen in the object and drive the Planning process, given the task requirements and object properties. The Setting Up Phase seems to demonstrate two different subphases. The first gets the hand posture 'in the ballpark'. During preshaping, the hand is driving the arm using anticipatory mechanisms and the hand is shaping according to the opposition space chosen. At the same time, the palm is being oriented. Then, after maximum aperture the hand encloses, a guarded movement involving feedback control anticipates tactile contact. The goal of setting up an opposition space is the alignment of the grasping surface patches of the hand with the seen opposition vector, given the opposition space parameterization appropriate for the task. The Using Phase is complex, involving rich interactions between vision, haptics and proprioception for controlling the hand, arm, and object. Movement seems to be driven strongly by sensory information and sensory consequences. Contact triggers a controller which uses active touch and controlled slipping to capture the object into the hand. Subgoals caused by the environmental goal can dominate in this phase, determining the influence of sensory information on the motor task; e.g., to hold a glass, a subgoal would be to squeeze fingers if the object is slipping, whereas to twirl a baton, a subgoal would be to reposition fingers if the object is slipping. The Releasing Phase is another example where feedforward anticipatory mechanisms seem to dominate, although it is unclear if the arm is driving the hand, the hand is driving the arm, or they are totally uncoupled.

There is a distinction between free motion and compliant motion. This distinction permeates the planning and selection of opposition space parameters through to the motoneuron recruitment patterns and muscle contractions for the application of functionally effective forces to grasp and manipulate objects. Once an object is grasped stably, the transport of the object can be viewed as a free motion with a 'loaded' limb. When the grasped object is being placed, the compliance of the supporting surface comes into play. Replacing the object on a support surface constitutes another guarded motion.

Opposition space analysis has vector description of motions and forces. During free motion (trajectory related planning), the vectors are concerned with directions and distances within a polar coordinate system. Direction and distance appear to be parallel dimensions. In contrast, during compliant motion (force related planning), the vectors specify directions and magnitudes of forces to be applied, in a palm centered coordinate frame. Here direction and magnitude of forces may be different dimensions as well. In setting up an opposition space, the opposition vector determines the directional planning for the hand configuration (i.e., driving the location and orientation of the grasping surface patches, with respect to the plane of the palm), yet the magnitude of forces is not mapped on until after contact has been made. During this time, there is a complex interplay probably of the most sophisticated type between kinesthetic, tactile and motor processes, and sensorimotor integration. The sensorimotor integration process relates to findings in peripheral receptor physiology (at the joint, muscle and skin receptor level), motor physiology (in terms of alpha and gamma motorneuron populations and spinal circuitry), and neurophysiology (reaching circuitry in the cervical spinal cord that parallels locomotor circuitry), and has important implications for the design of artificial manipulators.

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Part III

CONSTRAINTS AND PHASES

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Chapter 8. Constraints on Human Prehension

"Our hands become extensions of the intellect, for by hand movements the dumb converse, with the specialized fingertips the blind read; and through the written word we learn from the past and transmit to the future."

--Sterling Bunnell (1944)

The dextrous and versatile performance of human prehension can be viewed as emerging from a large multidimensional constraint space. Roboticists and experimentalists seem to be at odds currently in terms of the important variables examined in the quantification of motor control. It has been argued (Nelson 1983; MacKenzie & Marteniuk 1985; Marteniuk et al. 1987) that interactions are occurring among multiple performance constraints. Nelson (1983) argued that dynamic models, such as that of Hollerbach (1980), are inadequate for explaining human movement unless they also include both the performance constraints and the objectives affecting the neural and neuromuscular inputs. MacKenzie and Marteniuk (1985) described two types of constraints: those variables that constrain the use of feedback and those due to structural limitations that affect the preparation and execution of goal directed movement. Under the first category are included issues such as how fast feedback available, the types of feedback that can be used, and the experience of the performer in learning sensorimotor manipulations. In the second category are limitations from anatomical and neurological structure, from the structure of communicated information, the structure of environmental information, and constraints due to context and intentions. Marteniuk et al. (1987) emphasized the interaction between knowledge (which includes a person's experience and movement objectives) and the biological structure. Rewording the list of MacKenzie and Marteniuk (1985), Marteniuk et al. (1987) made even more explicit the notions of task constraints and conditions of speed and accuracy. Taking a task-specific view of movement planning and control, a task is defined as the interaction of the performer with the environment under given movement goals. This view predicts that movement is optimized and specific to the unique requirements that arise from an individual interacting with the environment.

In order to study the complex interaction between movement goals, object properties, environmental characteristics, and the

Table 8.1 Sources of constraints on grasping. Movement constraints and goals act to limit the way the human hand can be controlled in prehension (from Iberall & MacKenzie, 1990; reprinted by permission.

Group	Level of Analysis	Examples
High Level	Social/Cultural	don't stick out elbows; stick out little finger
	Motivational	thirst; anger
	Informational	convey affection, anger
	Functional	don't drop object; manipulate object; 'move as quickly and as accurately as possible'
Physical	Object Properties	intrinsic (texture, surface length, weight, etc); extrinsic (location, distance, environment, etc)
	Biomechanical/ Mechanical	kinematics; dynamics; limitations on force generation due to bones, muscles, tendons, ligaments, skin; effect and use of pads
Sensori-motor	Neural	temporal and spatial limitations on CNS; pyramidal tract needed for fractionated finger movements; sensory info needed to sustain movement; sensory information needed to preshape hand; tonic vibration reflex
	Perceptual	types, locations, and response characteristics of receptors; numerous tactile receptors in pulps with small receptive fields
	Anatomical/ Physiological	structural limitations on movements, directions, and extents; length of phalanges; additional muscles in index and little finger; pads; anatomical couplings
	Evolutionary/ Developmental	evolutionary pressures; five fingers; pyramidal tract develops in about eighth month

performer's biological structure and experience, it can be argued that there are different levels of analysis within this constraint space. These constraints, or levels of analyses, are grouped here into three broad categories, as seen in Table 8.1. This list expands and reorganizes the constraints listed in MacKenzie and Marteniuk (1985) and Marteniuk et al. (1987). The key point is that the list brings in the notion that higher level goals work together with harder constraints, as well as suggests ways that a roboticist's view of prehension can be integrated with a kinesiologist's view. For example, when a roboticist studies the constitution of a stable grasp, she is detailing the constraints imposed by an implicit functional goal 'to not drop the object.' On the other hand, when a kinesiologist tells a subject to 'move as quickly and accurately as possible', these instructions impose constraints on how to plan and effect the movement, given the person's biomechanics and sensorimotor constraints. Even physicians, when evaluating impairment of hand function, make distinctions between physical and functional evaluations (Swanson, Hagert & Scanson, 1983). Having the multiple constraint influences acting on prehensile systems, roboticists can develop higher level robot languages for control of more sophisticated dextrous robot hands, and kinesiologists can further refine their models of human performance using the tools provided by roboticists.

The constraints shown in Table 8.1 are discussed in the next section in terms of the three levels of analysis. Then a model is suggested for capturing human prehensile versatility.

8.1 Physical constraints

The laws of physics, captured in a variety of equations, create limitations on the planning and control of prehension. Whether the CNS solves these equations directly or not, they detail the meaning of movement within inertial reference frames and the effects of making contact with the environment. In the example where the functional constraint is to 'not drop the object', a posture must be chosen that effects a stable grasp. The three requirements for a stable grasp are (Fearing, 1986): 1) the object must be in equilibrium (no net forces and torques); 2) the direction of the applied forces must be within the cone of friction, which is twice the angle between the arc-tangent of the coefficient of static friction and a normal to the surface; and 3) it should be possible to increase the grasping force's magnitude to prevent any displacement due to an arbitrary applied force. Creating a stable grasp means taking into account active forces and torques as well as passive ones caused by the frictional components of the skin contacting the object surface. In addition, counteracting forces must be separated into their grasping and manipulation components (Yoshikawa & Nagai, 1990). If the applied force is too powerful, there is an unnecessary waste of energy; however, what is being optimized in human systems is a question (Nelson, 1983).

Although useful, sensory information is not a necessary condition for effecting a stable grasp. In robotics, Mason (1985, 1986) has shown that there are predictable results when two fingers are about to grasp an object even though there is some object position uncertainty. For example, in picking up a glass with the right hand, if the index finger makes contact before the thumb, the glass will rotate out of the grasp if the direction of the line of pushing (a line parallel to the motion of the finger, drawn through the contact point) is to the near side of the center of mass between the glass and the table. If, instead, the line of pushing is through the center of mass or to the far side, the glass will translate towards or rotate into the thumb, respectively.

Hand postures afford different ways to apply forces. Biomaterials such as bones, muscles, tendons, ligaments, and skin create limitations on static and dynamic force generation. Chao, Opgrande and Axmear (1976) argued that typically used postures are ones where joints are stabilized and where forces can be applied optimally without undue stress and strain on the ligaments, joint capsules, tendons, and muscles. An example would be locations where articular surfaces coadapt, thus permitting increased force generation while decreasing stress on ligaments and muscles. Results from cadaver studies have been used to develop and verify computer models of the mechanisms used by muscles and tendons to generate force across the various joints for different isometric hand postures (An et al., 1985; Chao et al., 1976; Cooney & Chao, 1977; Wells, Ranney & Keeler, 1985). Extrinsic finger flexors (as seen in Appendix A, forearm muscles that insert into the phalanges by sending long tendons through the wrist and hand) have a greater mechanical advantage than the extrinsic extensors (Tubiana, 1981). Within the hand, the intrinsic muscles of the index finger produce more force in a lateral pinch than in an enclosing grasp (An et al., 1985). The fingers and thumb have an average greater strength in a power grasp than in a pulp pinch (An et al., 1985; Cooney & Chao, 1977), particularly because multiple points of contact apply a force against the object. However, the size of the finger separation in the power grasp influences the gripping forces. In a task involving the isometric grasp of different size cylinders, Amis (1987) determined that the distal phalanx exerts the largest gripping (normal) force in all fingers, with a smaller force produced by the middle and proximal phalanges. Summing up these forces within a finger, the total normal force was largest for the smallest objects, and then decreased as the object size increased. Shearing forces at the distal and proximal phalanges for the index, middle, and ring fingers tended to pull the object into the grasp for smaller objects. As the object got larger, shearing forces on the middle and proximal phalanges tended to zero out, while at the distal phalanges, they tended to push the object out of the grasp. Other studies have analyzed the effect of wrist position on available force in precision and power grasps (Hazelton et al., 1975). Because the extrinsic muscles send tendons through the wrist, the amount of force that the fingers are able to apply is greater in wrist extension and/or ulnar deviation than in other positions. Hazelton et al. (1975) noted that the relative amount of force available at each finger during a hook grip remains constant across wrist positions (25% at the index, 33.5% at the long finger, 25% at the ring finger, and 16.5% at the little finger). Amis (1987) found the mean contributions to be 30%, 30%, 22%, and 18% to the overall grasp force. The lesson here (and further detailed in Section 8.2) is that there is a differential in the individual finger's potential contribution to force application, thus a factor in choice of postures.

Skin has properties that affect the frictional component of force generation. Typically, the law of static friction (Amonton's law) states that the tangential force, F_T, of friction is constrained to be no greater than the product of the normal force N with the coefficient of static friction, μ_S, or $F_T \leq \mu_S$ N (thus creating the cone of friction mentioned above). The coefficient of static friction, measured by various researchers (Buchholz et al., 1988; Comaish & Bottoms, 1971; Westling & Johansson, 1984), involves an interaction between the constraints of the skin surface and object surface (see below for discussion of object properties). Comaish and Bottoms (1971) found that the hand's palmar surface has a higher coefficient of static friction than the back of the hand. Buchholz, Frederick and Armstrong (1988) show that the coefficient of static friction increases when moisture is present, a situation that occurs particularly when the sweat glands of the palm are activated. Comaish and Bottoms also found that with some surfaces, the coefficient of static friction increased as the contact area increased (which would imply that Amonton's law is not the best model to use here, because it says the coefficient of static friction is dependent on the magnitude of the forces, not the amount of contacting area). Interestingly, the coefficient of static friction decreases with increasing load, reducing the effectiveness of friction for heavier objects (Buchholz et al., 1988; Comaish & Bottoms, 1971).

The frictional component of force generation is further enhanced when the pulps on the distal palmar surface of the fingers are used. These are highly specialized for prehension in that they provide friction, due to the epidermal ridges and to the sticky self-lubricating excretions through the tops of the ridges, and that they to comply with (instead of being displaced by) objects touched in the environment (Glicenstein & Dardour, 1981; Quilliam, 1978; Thomine, 1981).

While their existence is more an aspect of the hand's anatomy (see Section 6.1), their use in a prehensile posture is such that they can automatically supply a force sufficient to counteract small amplitude perturbations of the object, useful in stable grasping (along the lines of a 'soft finger' as a contact type that resists moments about the contact normal (Salisbury & Craig, 1982). The lubricant is greasy, having good adhesive qualities at low shear velocities, enhanced by the hills and valleys of the ridged surface extending the total shearing surface area (Moore, 1975). At high shear velocities, friction is reduced, thus minimizing wear and tear of the hand surface. Because ridges are concentric in orientation, there will always be some perpendicular to the force exerted (as opposed to in the palm where this is not true). However, due to biomechanical properties, skin responds in nonlinear ways to loads (Wilkes, Brown, & Wildnauer, 1973). As the load increases, collagen fibers in the dermis reorient from an irregularly arranged pattern to one orientated in the direction of the applied load. As more fibers become aligned and thus resist extension along their length, the skin becomes stiffer, reducing its ability to comply with the object.

Object properties and the object's relationship to the environment can affect the chosen posture. Jeannerod (1981) made a distinction between intrinsic and extrinsic properties of objects. Extrinsic properties are those spatially related to the person (i.e., location, distance, angle, etc.) and would include support constraints, such as a table supporting a surface, and other obstacle constraints (forcing one to reach around another object). Lederman and Klatzky (1987) have shown how subjects can extract intrinsic object properties relevant to the task. These include surface properties (texture, hardness, and temperature), structural properties (shape, volume, weight), and functional properties (part motion, specific function). Before making contact with an object, people can perceive many object properties visually (see Klatzky & Lederman, 1990). In a study where subjects had to use a precision grip to grasp one of ten different sized wooden disks, Marteniuk, Leavitt, MacKenzie, and Athenes (1990) showed that the maximum aperture reached during preshaping between the index finger and thumb closely correlated with disk size. In terms of the constraints that object properties impose on prehension, examples are numerous: object shape can delimit grasp postures and the number of fingers potentially contacting a surface; the weight of the object can determine the type and strength of grip; and the availability of an object surface will constrain the orientation of the reach and potential contact locations.

Other object properties have an effect on force generation as well. Cochran and Riley (1986) found that handle shape affects the force exerted: higher forces were seen with irregularly shaped handles (rectangular and triangular) than with uniformly shaped ones (circular). Westling and Johansson (1984) looked at precision grasping of objects with different textures and different weights. If the object's surface texture is sandpaper, then there is a higher frictional component to the interactive forces than if the surface texture is suede or silk. They looked at the ratio between the grip force (force normal to the object's surface) and the load force (force tangential to the object surface in line with gravitational force). The value for this ratio below which the object will slip out of the fingers is called the slip ratio. Johansson and Westling found evidence that subjects maintain a safety margin above this ratio, and even use one of two strategies for maintaining a safety margin: either the safety margin is a constant fraction or else a constant absolute value of the grip force. While the slip ratio is a physical constraint, maintaining such a safety margin above it is a functional constraint, imposed by some goal of the performer (in fact, for Johansson and Westling to measure the slip ratio, they had to request that their subjects 'slowly separate the thumb and index finger until the object drops', which is a difficult task to perform).

How the CNS actually obtains task relevant object information is a function of the interaction with the object. Klatzky and Lederman (1990) have shown that subjects use their hands in particular ways to extract the sensory information needed in a task. For example, lateral motion is used to extract texture information and unsupported holding is used for extracting weight information. Even though a procedure is specialized for just one dimension, it is still informative along others. For example, contour following is used specifically to extract exact shape and volume, but it can also extract sensory information for all the object properties they measured. While a slower process than the more specialized ones, contour following nevertheless is a procedure typically observed in prehension. In an informal mug grasping study (Arbib, Iberall, & Lyons, 1985), the subject's fingers were seen to move along the inside of the handle while capturing the object into the grasp, thus perhaps providing to the CNS additional knowledge about the texture, hardness, temperature, and weight of the mug.

In summary, prehensile behaviors are subject to the constraints imposed by the laws of physics. A dextrous, multi-fingered hand is not constrained at this level of analysis to unique prehensile postures for a given object. In the next subsection, the constraints explicitly imposed by the sensorimotor system are discussed.

8.2 Sensorimotor constraints

The hand of *Homo sapiens sapiens* represents millions of years of evolutionary pressures, changing it from a tool of tree-dwellers into what it is today. Holder (1983) noted, from studying 145 limb skeletons of amphibians, reptiles, birds, and mammals, that the overall pattern of skeleton and muscles has varied little in 350 million years, even though the limbs have become adapted for different functions. LeGros-Clark (1959) noted the development of the pentadactyl (five-fingered) hand, the replacement of claws by nails, and the specialization of the finger pads. Other signs of refined functionality have been noted as in tendon insertions (Abbott, 1970), the remodeling of joints (Lewis, 1977; Marzke, 1983), and intradigital proportions between phalanges (Musgrave, 1971). A functional axis of a primate hand can be distinguished by various criteria (Rabischong, 1981) such as along the longest finger or at the insertion of the dorsal interossei muscles (intrinsic hand muscles that abduct the fingers). In the human hand, two dorsal interossei insert into the middle finger making it the functional axis of the hand. However, it is interesting to note that the head of the 4th metacarpal (see Appendix A.2), unlike its counterparts in the other fingers, is symmetrical, suggesting instead that the ring finger may be the functional axis of the hand (Dubousset, 1981). These, and other characteristics of hand structure, such as the presence of five fingers, are evolutionary constraints in the sense that they have modified the organization of prehension over the eons (see LeGros-Clark, 1959 and Napier, 1962 for further reading). Today, as one moment in time, they have left the human hand with a variety of highly asymmetrical anatomical and physiological features and constraints.

The anatomy and physiology of the hand and arm create structural limitations on possible joint configurations, movements, directions and extents. In the robotics literature, the directions and extents of movements are referred to as the 'workspace'. In the human literature, the region of extrapersonal space where prehension may occur has been termed 'grasping space' (Grusser, 1986). Grasping space is a function of motion about the shoulder and about the elbow and wrist joints of the arm, given that the body is stationary.

Although the hand has over 25 degrees of freedom, many are coupled by the nature of the ligamentous structure and location of tendon insertions (Kapandji, 1982). For example, although each finger has four degrees of freedom, they are not individually controllable. The flexors tend to work together (Tubiana, 1981): when the index finger begins to close in toward the thumb in a precision grip, the flexion of the proximal interphalangeal joint (see Appendix A) releases tension on the retinacular ligament, allowing flexion of the distal interphalangeal joint. Flexion of the proximal interphalangeal joint puts the intrinsic muscles under tension, initiating flexion of the metacarpophalangeal joint. In another example, the intrinsic lumbrical muscle runs from the extrinsic flexor tendon to the extensor tendon and plays multiple roles in flexion and extension (Ranney & Wells, 1988). It is primarily responsible for interphalangeal joint extension, which it does by decreasing the flexor force. Because of its attachment to tendons moving in opposite directions and the great number of muscle spindles (sensors), Ranney and Wells suggested that the lumbrical muscle monitors the rate of hand closing during grasp.

Other aspects of the muscular system show distinguishing workspace characteristics. An obvious feature is the increased mobility of thumb and its placement on the palm, both of which enable its opposability to the fingers. While the tendency is to think only of the thumb as being unique, there are distinguishing features among the fingers besides their differential size and contribution to force generation. While the extrinsic extensors going to all four fingers have a common origin in the forearm, additional extrinsic muscles to the index and 5th fingers give these fingers more independence of movement (Kapandji, 1982). The 5th carpometacarpal joint, with a mobility of about 25 degrees, has a unique intrinsic muscle that allows the palm's shape to be modified for complying to a variety of object shapes. The differential action of the fingers is seen in the composite distal palmar crease (Bunnell, 1944): the most distal of these creases (i.e, the 'heart' line in palm reading) is related to the action of the middle, ring, and little fingers in opposition to the thumb; the more proximal crease (the 'head' line) is related to the action of the index, middle, and ring fingers. Bunnell also notes that the palm, having webbing between the fingers, is broader and longer than the back of the hand.

A final feature of the hand's anatomy is the skin and the underlying fatty pads. Skin consists of multiple layers and tissues, notably the outer epidermis and inner dermis (Thomine, 1981). Palmar skin, which is thick, tough, resistant to pressure, and good for complying with objects, can be contrasted with dorsal skin, which is fine, supple, and does not impede mobility in flexion. The palmar skin, unlike the dorsal skin, is covered with epidermal ridges and exocrine sweat glands, and contains malleable 'fat pads'. At the distal ends of the fingers and thumb are the specialized pulps (Glicenstein & Dardour, 1981). Shearing forces at the pulps are resisted by strong interdigitating folds between the epidermis and dermis, where interpapillary ridges prevent the epidermis from sliding over the dermis (Quilliam, 1978). The dermis is further anchored to the connective tissue around the bone of the distal phalanges with fibrous connections. It is particularly noteworthy that the trajectory followed by the fingers during thumb opposition brings the finger pulps into the same plane as the thumb pulp (Kapandji, 1982). In perturbation studies of rapid pinch movements, Cole and Abbs (1987) observed that subjects consistently brought the finger pulps into contact although that was not part of the task instructions. For subjects to do this in response to the thumb perturbation, it required the reciprocal adjustments at two index finger joints, an adjustment more complex than a single joint one. The reason for this could be due to a higher level goal (see Section 8.3).

In terms of the nervous system, its anatomy and physiology create temporal and spatial physical limitations. The types of receptors (both cutaneous and proprioceptive), and their spatial and temporal response characteristics, serve as constraints in the control process. Studies analyzing the motor response to tactile sensory information show low level interactions. Torebjörk et al. (1978) presented evidence that a tonic vibration reflex can cause the fingers to flex. In this study, they placed a small motor against the finger, causing the finger to vibrate. They found that all subjects increased their finger flexion force against a small plate, in a frequency-dependent way. Torebjörk et al. argued that the signals from particular skin mechanoreceptors could be involved in such a motor response. Numerous tactile receptors are found in the finger pulps, more so than most other parts of the body, thus giving the CNS much information about the object with which they come into contact (Vallbo & Johansson, 1984). These mechanoreceptors are classified by their adaptation response to sustained skin deformation and the structure of their receptive fields. Receptors having small and well-defined receptive fields are especially dense in the finger pulps. Westling and Johansson (1987) observed that at higher grip forces (when the skin is less compliant) these receptors are less responsive. In terms of proprioception, receptors in the muscles, tendons, and joint capsules signal the CNS about the current state of the limb (McCloskey, 1978). An interesting result relevant to prehension shows altered muscle spindle sensitivity (i.e., dynamic changes in 1a afferent firing patterns) with flexion and extension of the hand (Edin, 1988). This could possibly play an important role in hand preshaping.

Constraints exist on the speed/timing of sensorimotor integration. Sensory information appears to adjust ongoing movements in less time than previous estimates of visual reaction time, estimates in the range of 190-260 ms (Keele, 1968) or 120-200 ms (see Schmidt, 1988). Cole and Abbs (1988) have shown responses in grip force of the index and thumb having a latency of 60-90 msec after onset of an increase or decrease in load force. The changes were dependent on the size and velocity of the perturbation force and independent of the original grip force level. The latency is longer than a monosynaptic reflex but shorter than the reaction time estimates, reflecting a rapid, automatic mechanism responding specifically to unexpected load force changes and not maintaining a preferred safety margin. They showed that this depends on cutaneous stimulation such as increased shear forces at the digital pulps due to object slips. One possible explanation is that sensory information is being used here for triggering a response, instead of as feedback for modulating a response.

As well, availability of a sensory modality can affect movement. Movements occur differently depending on the availablity of the sensory information. An example is seen in a patient having a lesion in the parietal area of the cerebral cortex who could not preshape her hand while reaching to grasp an object, because she lacked somatosensory information (Jeannerod, 1986). Once the hand was within view, the patient using visual guidance could open her hand and grasp the object, although she was still unable to apply the correct grasping forces. Peripheral nerve damage can influence behavior as well (Rothwell et al., 1982). The patient in this study could initiate grasping tasks, but a stable grasp could not be maintained. He could not perform automatic reflex corrections in voluntary movements, nor could he sustain levels of muscle contraction without the use of vision. Johansson and Westling (1987) have shown that as human subjects pick up objects, microslips occur beneath the conscious awareness of the subject; that is, the object slips slightly in the grasp as the object is lifted. Recording from the median nerve, Johansson and Westling demonstrate that sensory information about the object's state is being transmitted into the nervous system. The microslips are reduced to zero as the force level is adjusted and balanced to the frictional conditions, stabilizing the object in the grip. The Rothwell et al. patient, having lost access to microslip information, cannot make low level fine adjustments. These data suggest physiological limitations on prehensile movements, specifically on the underlying sensory and motor pathways.

Other types of damage to different neural substrates constrains available grasping behaviors. It has been shown that cutting the pyramidal tract, which is a direct pathway between various cortical areas and the motoneurons in the spinal cord, results in the loss of fractionated finger movements (Lawrence & Kuypers, 1968a,b). Primates can still perform collective hand grasping movements because less direct pathways are still intact, but are unable to oppose thumb and fingers. One other aspect of the nervous system lies in the issue of sensorimotor representations (c.f. Iwamura et al., 1981). While the motor and somatosensory cortical representation for the hand is quite large, the type of processing is still not known.

In summary, human prehensile behavior is further constrained by anatomical and physiological aspects of the body and nervous system, just as robots and their computer controllers are constrained by their construction and interfaces. However, without a 'reason' for the movement, which in itself can constrain the formation and modulation of the movement, there would be no need for this complex machinery. Therefore, higher level goals are discussed in the next subsection.

8.3 High level constraints

At the highest level, four classes of constraints in living systems can be grouped together. These constraints are imposed for a variety of reasons. The importance is that there are probably large individual differences. They are labeled here as follows: semiotic/informational, motivational, social/cultural, and functional/intentional.

Semiotic, symbolic, or emotional information may be conveyed in the way an object is grasped (Nespoulous & Lecours, 1986). For example, one might hold a cigarette in a suggestive manner. Anxiety or anger may be communicated by gripping an object tightly. Motivations, such as needs being satiated, may add an urgency to the movement. As well, sociocultural constraints create boundaries on acceptable behavior. Refined behavioral interactions with objects in one culture might be taboo in another. For example, sticking out the little finger as one grasps a teacup may be a sign of good upbringing in a culture (see Section 8.2 for a possible anatomical reason). On the other hand, sticking out one's elbow while reaching might be an invasion of someone else's extrapersonal space.

While these are merely anecdotal evidence for such effects on prehension, kinesiologists and psychologists have begun to explore the functional issues. Movement constraints act within and around the intentions of the performer, which delineate goals for a movement. An example would be the 'sherry-glass response' (Traub, Rothwell & Marsden, 1980). Subjects were asked to maintain their thumb and index finger a few millimeters from the rim of a full glass of sherry. A perturbation was made to the wrist sufficient to cause the hand to hit the glass and knock it over. A short-latency grab response (50 msec) occurred in the thumb muscle in response to the perturbation, thereby saving the glass from being knocked over. However, the response was observed only when the subject's intent was to prevent the glass from falling over. Traub et al. argued that this suggests the presence of a grab reflex, where the digits respond within a time too short to be voluntary, flexing in order to maintain contact but only if contact is the person's intent.

In a formal empirical situation, intent emerges from the experimenter's request to the subject to perform a certain task. In MacKenzie et al. (1987) for example, the subjects were asked to point with a stylus 'as quickly and as accurately as possible' to a target of varying size and at varying distances. The question being asked was whether there was a reliable kinematic measure of the speed and accuracy requirements of the task. In this case, Fitts' Law (Fitts 1954) was used, which states that movement time (MT) is directly proportional to the index of difficulty (ID) of the task, or MT = a + b x ID where the ID is the $\log_2(2A/W)$, A is the amplitude of movement (an extrinsic object property), and W is the width of target, or target tolerance (an intrinsic object property). When plotting MT against ID, a linear relationship is seen. MacKenzie et al. (1987) measured the MT of the tip of the stylus, its time to peak resultant velocity, and the percentage of movement time after peak resultant velocity. They found a differential effect of target size and amplitude on these parameters. For each target size, the acceleration time increased as the ID (amplitude) increased. For each amplitude, there is no effect of target size on the acceleration time. When the data was normalized, the percentage of MT after peak resultant velocity (the deceleration phase) increased for each amplitude as the ID increased (target size decreased). These results indicate that the resultant velocity profile is not symmetrical. Fitts' Law argues that the MT will increase as the target size decreases; the reason that the MT increases is the result of a relatively longer deceleration phase. As well, for longer movements, there is a longer acceleration phase. The results show that the time spent in the deceleration phase was predicted by ID as well or better than MT. This was not the case for acceleration time. Only movement amplitude affected the time to peak velocity. Thus, amplitude and target size effects were dissociable in that the shape of the tangential velocity profile was a function of target size (accuracy), and the peak speed along the path of the trajectories was scaled according to movement amplitude.

In grasping and aiming tasks (Marteniuk et al. 1987), precision requirements were varied, showing how intention, context, and object properties affect timing parameters of prehensile movements. The first experiment varied goal (pointing to a target or grasping a disk); the second one varied object properties (grasping compliant tennis ball or fragile light bulb); the third one varied movement intent (placing or throwing an object. Using Fitts' Law to equalize the ID's, it was observed that the grasping took longer than pointing. The percentage of time in the deceleration phase was longer for grasping than pointing, for grasping the light bulb than grasping the tennis ball, and for placing than throwing. They argued that all these effects could be due to the requirement for 'precision'. Fitts' Law predicts that MT increases with aiming precision requirements, but they demonstrate this increase is due to the lengthening of the deceleration phase disproportionately to the rest of the movement. As well, they show other influences, such as object properties and task intent. Less variability between conditions was seen in the early or acceleration phase of the movement, and more variability during the deceleration phase. They argued that the early part of the movement is more likely to be directly influenced by central stereotyped movement planning or programming, while the later part of the movement, during the deceleration phase, uses more sensorimotor adjustments for controlling the movement, causing more variability. Increasing precision requirements of a task may induce subjects to use more sensory information, particularly in the 'homing in' part of the task. This relates to Jeannerod (1984), where it was argued that an initial ballistic phase places the hand into the vicinity of the target, and a second phase using feedback guides the hand to the target. It is interesting to note that in pointing tasks, where subjects pointed to imaginary targets in space, velocity profiles are symmetrical (Atkeson & Hollerbach, 1985).

Another dimension to task requirements, in contrast to precision, is the anticipated forces acting in the task. In Iberall et al. (1986), an informal study is reported to observe the effect of anticipated forces on the posture chosen to grasp a vertically standing dowel. Subjects were asked to pick up the dowel and either to place it on a marker or to shake it. It was observed that in the less forceful, more precise placing task, the subjects used precision grasps. In the more forceful, less precise shaking task, the subjects initially used a precision grasp to lift the cylinder, and then adjusted their posture into a more powerful posture once the cylinder was lifted. The posture chosen appeared to match the forces currently acting in the task. During the lifting phase in both tasks, only the light weight of the cylinder was in effect, and therefore the subject used a precision grasp. The subjects did not use the more powerful posture before it was necessary.

In summary, people grasp objects with specific objectives. Once the objective is established, such as to achieve some functional goal, to convey some information, or to satisfy some internal motivations, the movement can be carried out within socio-cultural guidelines. While goals in the strictest sense are not constraints (people do drop objects), their effect on human prehensile behavior can be seen in the selection of movement parameters and the choice of prehensile postures. Because multiple grasping solutions are possible, the controller is faced with the question of how best to use hand features, in relation to the anticipated object properties and predicted interaction outcome, in order to achieve the goals of the task.

8.4. Mapping Opposition Space into Human and Robot Hands

An opposition space describes a hand posture as a collection of virtual fingers able to apply functionally effective forces against an object for a task. Real fingers group together into a virtual finger to apply an opposing force against other VFs or against task torques. Selecting an opposition space identifies a goal posture that closely resembles the posture taken on in contacting the object (Marteniuk, Leavitt, MacKenzie, & Athenes, 1990). The 'preshape posture' consists of combinations of oppositions and virtual-to-real-finger mappings that are to be used in the task. As detailed earlier in Chapter 2, each VF has state variable that describes it:

a) VF length (from the center of the grasping surface patch to the joint where it connects to the palm)
b) VF orientation relative to the palm
c) VF width (number of real fingers mapped into the VF)
d) orientation of the grasping surface patch (the orientation of the applied force)

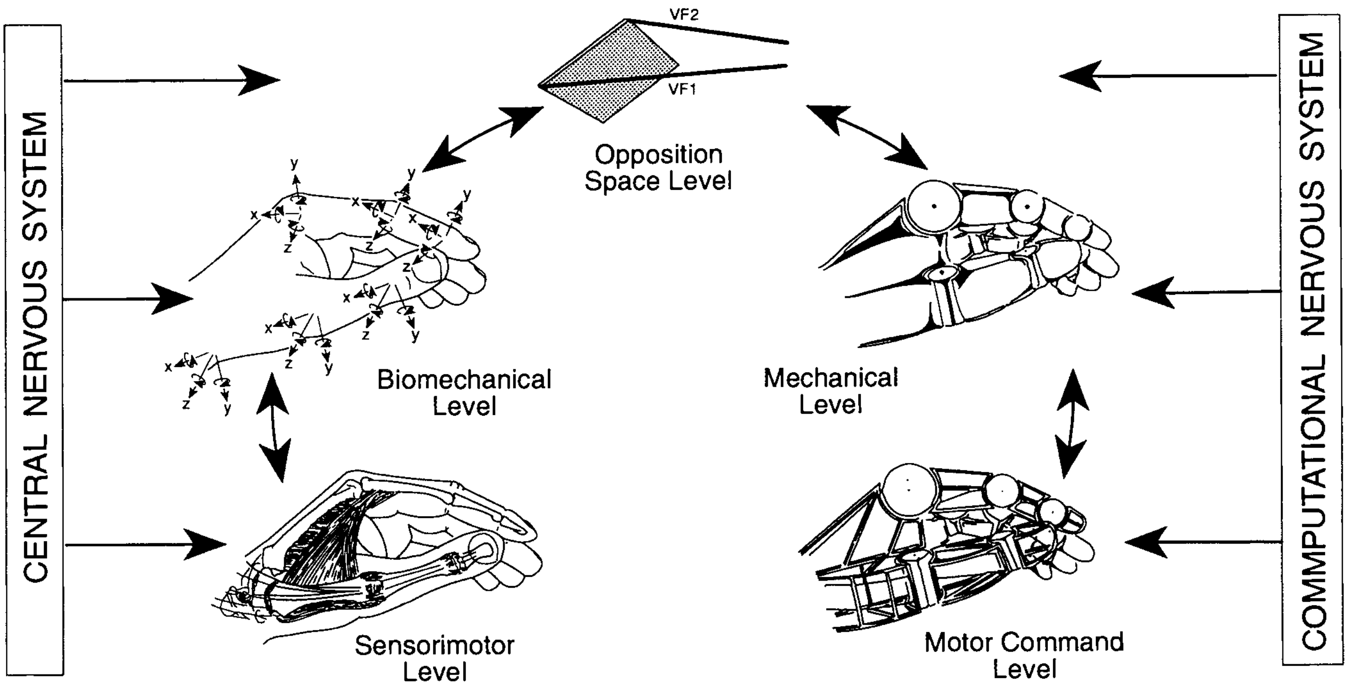

Figure 8.1 Levels of mapping. An opposition space describes a hand posture in terms of VFs and opposition parameters. These are constrained by contact and joint forces and torques at the Biomechanical and Mechanical level. These are further constrained by muscle activation and motor commands, integrated with responses from surface and internal sensors at the Sensorimotor and Motor Command level. A controller chooses an opposition space that both satisfies the requirements of the task as well as the constraints imposed by the hand.

e) amount of force available from the VF (mean, maximum, minimum)
f) amount of sensory information available at grasping surface patch (innervation density of cutaneous mechanoreceptors)

VF vectors are tagged with the orientation of the grasping surface patch at a given configuration. For example, in pad opposition, the grasping surface patches are the finger and thumb pads. As the VF vectors change length and orientation during flexion and extension, the pads are changing orientation relative to the palm. The grasping surface patch size depends on the number of real fingers being used in the VF and the amount of their abduction, as well as on the configuration. In terms of state variables, an opposition spaces is defined by the following state varibles:

a) the number and type of oppositions (pad, palm, and/or side) being used,
b) the virtual to real finger mapping (i.e., which fingers),
c) VF state variables for each VF in each opposition being used (see above).

Of course, this goal posture only makes sense within the constraints of the hand itself.

Using Marr's approach (see Chapter 1) as a guiding principle, the Opposition Space level can be re-represented or mapped into a Biomechanical level (Figure 8.1). At this level, opposition space parameters are re-represented in terms of the forces and torques acting at the joints and contact points. Inverse kinematic and dynamic equations translate VF parameters into real joint angles and torques. For example, if one objective of the movement is to 'not drop the object', the opposition space chosen for the grasp must effect a stable grasp, taking into account the active and passive components of force generation by the muscles, tendons, and skin surfaces. In addition, the chosen posture must relate to stress and strain on biomaterials and take into account mechanical advantages. Using pad opposition, the enhanced frictional component of the finger pulps helps in reducing the amount of active force. However, if the object is heavy and/or if there is a low coefficient of friction between the skin and object surface, the posture involves a different opposition space, one where active available forces are larger. A palm opposition, having multiple phalangeal contact points and greater strength, would be used. As well, the palm, as a large virtual finger, brings in a torquing component to a prehensile posture, if so needed in a task. The tradeoff for this extra power is in not having the finger pulps in contact with the object; a compromise would be to use a combination of side and palm opposition, where the thumb pad contacts the object and applies a force transverse to the palm. If the task goal is to 'move as quickly and as accurately as possible', timing parameters are chosen consistent with Fitts' Law while also consistent with kinematic and dynamic constraints acting on the hand and arm. Not only must the anticipated forces be matched, an opposition space must be chosen that allows perceptual systems access to the information needed to ensure the accuracy requirements. Accuracy suggests pad opposition, but only if the forces are not too great. With greater forces, one compromise is to use more fingers in the VF opposing the thumb.

The final mapping to be discussed from the Opposition Space level (Figure 8.1) is the Sensorimotor level. Opposition space parameters are re-represented at this level in terms of the activation level of the muscles and receptors acting on the fingers, which, in effect, is the implementation level. Anatomical constraints, for example, limit the number of ways real fingers can be mapped into VFs. The task goal of 'not dropping the object', expanded by the ways that forces can be generated to achieve the goal, is further translated into a posture that judicially uses the skin mechanoreceptors, optimally placing the pulps, with all their receptors, against the object. The chosen VFs must have adequate sensory resolution and sensitivity at the contact points. With large task forces, pad opposition would not be effective due to loss of skin sensitivity and lack of muscle strength. Being able to anticipate much of the object's behavior upon contact allows part of the choice to be influenced by the VF parameters that will correctly position task-specific sensors for triggering the next action. If the object starts moving, the tonic vibration reflex will force the fingers to close tighter. Perhaps in contour following, where the fingers are moving instead of the object, similar principles apply. The advantage of performing contour following is that one gains additional knowledge about the object's various properties, and the fingers can perhaps be better placed for effecting a stable grasp. If palm opposition is used in order to handle the larger forces, the posture still gives information about the object state, particularly because the palm can adapt to the object's shape and therefore place more skin surface in contact with the object. In terms of constraints on the mapping from virtual to real fingers, there are significant distinctions in how the individual fingers contribute to prehension (number of muscles, types of articular surfaces, lengths and widths of phalanges, type of support at wrist, etc.). Affecting the choice of an opposition space, intrinsic and extrinsic muscles make differential contributions to movement, while muscle, tendon, and joint receptors provide information about results of those movements. The existence of low level sensorimotor features -- such as the tonic vibration reflex, pad alignment in opposition, coupled degrees of freedom in the fingers, ligaments being used for passive control, and rapid grip force adjustments -- and higher level neural control, such as active control of muscles and the pyramidal tract for fractionated finger movements are noted.

Opposition space as a model takes into account the hand's ability to be both an input and output device, dealing with applying task forces while gathering sensory information. It addresses the hand in terms of its oppositional capabilities, providing combinations of oppositions and VF mappings that match the requirements of the task. Two important benefits to using a Marr type view for prehension are observed. On one side, it separates implementation details from a task description, a trend occurring in programming languages in general, and robot programming languages in particular. This allows the functional study of human hand to be carried over to dextrous robot hands. The mapping from opposition space into the human hand, with its particular physical/biomechanical and its sensorimotor constraints, can be replaced with a robot hand that has its own mechanical and motor constraints (Figure 8.1, right side). The human Central Nervous System is replaced by a Computational Nervous System, comprised of an expert system, feedforward and feedback controllers, and/or software simulating a neural network. Or perhaps it could be a hardware implementation, such as a distributed network of computers, transputers, RISC processors, or even neural network hardware. The mapping from actual to robot hand changes without redoing the overall high level description of hand functionality. Of course, until a robot has a reason to grasp an object, other than being told to do so, the only high level effects would be functional ones.

The advantage of this model is that movement occurs satisfying all the constraints acting on the system. Goals from the upper level filter down while the constraints from the biomechanics and anatomy filter up. This allows an opposition space description to be device independent, and therefor, the postures of the human hand can map onto other manipulators. Motor commands are generated at three levels (opposition space, biomechanical, sensorimotor) and act within a constraint space of possibilities.

Another issue is the goal to understand the versatility of human prehension in general. With a large repertoire of available movements, and the potential use of many prehensile strategies at one's disposal, the choice for using one strategy over another can be based on anything from physical laws to whimsy. Roboticists and experimentalists seem to be currently at odds in terms of identifying the important variables to be examined in the quantification of motor control. By identifying and separating hard physical constraints from softer functional constraints, the hope is to find ways to integrate the various views of motor behaviors.

8.5 Time Varying Constraints

One might ask whether or not the constraints listed in Table 8.1 are time varying constraints. Given the importance of time scale considerations in the adaptation process (A. S. Iberall, 1972; Piaget, 1953), each constraint must be analyzed in terms of whether it varies over the time course of the opposition space phases for a single grasp instance. Some of these are constant within the time scale of the reach and grasp. Other constraints may change within a person's lifetime of grasping objects. Finally, others may be changing on a much longer time span, over the course of evolution. For the case of a single grasp, the time span is in the second range, although longer grasps are possible (e.g., climbing, trapeze swinging). An important question to address for computational modelling is how these constraints might fit into an artificial network model. Possibilities include: acting as an input to a system, acting as a rule mapping the inputs to the outputs, or part of the structure of the network itself. Reviewing the constraints in terms of time scales:

1. **Social/Cultural**--not time varying within the time scale of the current reach and grasp. Can change within a person's lifetime, thus acting as an input, influencing the selection of the grasp and reach strategy.
2. **Motivational**--not time varying within the time scale of the current reach and grasp. Changes between grasps, thus acting as an input, influencing the selection of the grasp and reach strategy.
3. **Informational**--not time varying within the time scale of the current reach and grasp. Changes between grasps, thus acting as inputs, influencing the selection of the grasp and reach strategy.
4. **Functional**--not time varying within the time scale of the current reach and grasp. Changes between grasps, thus acting

as an input, influencing the selection of the grasp and reach strategy.

5. **Object Properties**--not time varying if inanimate or moving. Changes between grasps, thus acting as an input, influencing the selection of the grasp and reach strategy
6. **Biomechanical/Mechanical**--laws of physics, captured in a variety of time-varying functions, can become part of the processing algorithm (rule or function being computed).
7. **Neural**--Anatomy: not time varying within the time scale of the current reach and grasp. Can change within a person's lifetime, affecting the topology of the processing circuits. Physiology: time varying within the time scale of the current reach and grasp, affecting the processing algorithm (its implementation). Changes within a person's lifetime.
8. **Perceptual**--location and response characteristics of receptors not generally time varying within the time scale of the current reach and grasp. Changes within a person's lifetime, thus acting as an input, influencing the selection of the grasp and reach strategy.
9. **Anatomical/Physiological**--Anatomical: not time varying within the time scale of the current reach and grasp. Changes within a person's lifetime, thus acting as an input, influencing the selection of the grasp and reach strategy. Physiological: time varying within the time scale of the current reach and grasp, acting as inputs.
10. **Evolutionary**--not time varying within the time scale of the current reach and grasp or within a person's lifetime. Affecting the anatomy and physiology of both the arm/hand and topology/substrate of the brain.

Summarizing, the sources of constraints that are time-varying functions within a particular grasp are the biomechanical and the physiological aspects of the arm/hand and the brain. The sources of constraints that act as inputs into a decision process for selecting a grasp strategy are: hand anatomy, perceptual constraints, object properties, functional, informational, motivational, and social/cultural. Constraints that are part of the processing algorithm (Marr's level 2) are the (bio)mechanical. Constraints that are part of the processing implementation (Marr's level 3) are neural, anatomy, and physiology.

8.6 Summary

The versatile performance seen in human prehension emerges within a large multidimensional constraint space. There is a complex interaction between movement goals, object properties, environmental characteristics, and the performer's biological structure and experience. Even deeper is the evolutionary pressures on the hand and why it has taken on the form that it has, and what developmental needs constrain it further. The ultimate issue in this complex interaction is to match the task requirements (which one could argue incorporate a wide range of needs from social to motivational to informational to functional) to the capabilities of the hand (its sensorimotor capacity) given the physics of compliant motion. Functional goals can range from 'palm a coin to hide it from view' to 'don't drop the object' or 'move quickly and accurately.' Force production is affected by the chosen posture, the wrist angle, the mechanical properties of skin, the use of the fatty ridged pads, and the generation of sweat. Features of the hand contributing to its use in prehension include its numerous degrees of freedom, the thumb's mobility and placement, the mobility of the 5th carpometacarpal joint, the pads, and the placement and response characteristics of cutaneous and proprioceptors. Neural contributions specific to prehension include the pyramidal tract for fractionated finger movements, multiple representations of the hand and wrist in motor, premotor, and somatosensory cortex, grasp reflex, a grip force reflex, and contextual neural responses. The laws of physics that influence the interaction include stability, laws of motion, kinematics, dynamics.

One way to view the control of the hand is as a three-tiered model. This looks at how the sensorimotor level (anatomy and physiology of the limb, the peripheral nerves, and kinesthetic and cutaneous receptors) constrains the hand as a biomechanical device (forces and torques acting on the bones and joints in a given posture) which in turn constrains possible opposition space choices. In addition, identifying a desired opposition space, given functional constraints such as object properties and task requirements, sets up a goal posture. The goal posture can hopefully be met by some real posture without undue stresses and strains on the joints and bones that can in turn be met by the anatomical constraints. And this mapping can be done for the multiple phases of prehension. Separating the goals from the contraints serves two purposes. First, it identifies the direction of information flow, as goals are sent down and constraints are sent up. Secondly, it presents a method for mapping a device independent hand into other hands, such as dextrous robot hands and prosthetic hands. These devices would just need their own computational nervous system to perform the mapping that the central nervous system does for the human hand. The mechanical hand, while seemingly different (made of different materials, having different characteristic workspaces, etc.), must obey many of the same constraints (laws of physics, achieve goals). With a dextrous multi-fingered hand, multiple grasping solutions are possible, and only additional constraints will guide a controller in making choices. Each controller is faced with the question of how best to use its hand's features in relation to the anticipated object properties and predicted interaction outcome, in order to achieve task goals. By separating out levels of analysis, the study of human hand functionality can be related to dextrous robot hand functionality.

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Chapter 9. Reevaluation and Future Directions

"What do human hands do? Look around you."

--C. L. MacKenzie and T. Iberall (1994)

As we look around, we sit in wonder at the versatility of the human hand, the greatest tool known to humankind. Yet, as Frederick Wood-Jones (1920) pointed out, the structure of the human hand and monkey hand are very similar. Phillips (1986, p. 6) stated that,

> "the increasing versatility of hand function as we ascend the primate scale has been conferred by a progressive enlargement of cerebral cortex and cerebellum and a corresponding enrichment of their intrinsic and extrinsic synaptic connectivity".

This book has explored two questions: the question of what is the nature of the human hand and the question of what might be involved in the CNS as it controls this marvelous tool in prehension. Starting with the concept of a black box that takes inputs and produces results, experimental evidence has been examined for data that might suggest how the CNS selects prehensile behaviors for interacting with objects for a task, given numerous constraints. Computational models have been explored that make explicit the issues in motor control. The underlying theoretical framework was based on the model of the CNS as a parallel distributed processor using action-oriented perception and goal-directed movement.

In this chapter, we revisit the issues put forth in Chapter 1, summarizing key points made through the text. Our goal in writing this book has been to put forth a comprehensive study of human prehension, looking in depth at all the factors contributing to our primate ability to grasp objects. However, the careful reader will note many missing topics. Therefore, we take the opportunity in this chapter to outline other issues critical to the understanding of human prehension.

9.1 The Black Box Revisited

In Chapter 1, the concept of a black box was introduced as a way to study a complex behavior (see Figure 9.1). Using the working definition of prehension, that is, the application of functionally effective forces by the hand to an object for a task, given numerous constraints, inputs to the black box were identified as the object and task, while the output was prehensile behavior. Data from various scientific disciplines and simulations from the engineering sciences have been presented in order to shed light on the processing within that black box.

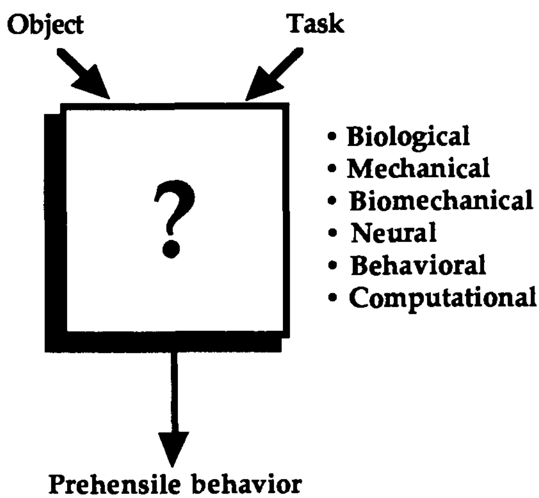

Figure 9.1 The black box revisited. Many levels of analysis are involved in understanding the complex intereactions between objects, tasks, and prehensile behavior.

9.1.1 Objects

In terms of the object, much evidence exists for what object properties are available to the perceptual system. These data have emerged from experiments in haptic exploration, visual discrimination, wielding and jiggling, intrinsic and extrinsic property perturbations. Two types of object properties have been studied: extrinsic and intrinsic object properties. Extrinsic object properties are spatial properties of objects in an egocentric body space. Extrinsic object properties, perceived visually, include orientation with respect to the body (Chan et al., 1990; Jeannerod & Decety, 1990), distance (Sivak & MacKenzie, 1992), and direction (Paulignan, MacKenzie, Marteniuk & Jeannerod, 1991). Neurally, Georgopoulos et al. (1988) showed that direction is encoded by a population vector in the motor cortex.

Intrinsic object properties are the physical identity constituents of objects, and include structural properties, such as shape, size, distribution of mass, and weight, and also surface properties, such as texture, temperature, and hardness. Intrinsic properties affect the selection of a grasp posture, as was observed in the discussion on grasp taxonomies in Chapter 2. For example, the shape and size constrains the type of opposition used, how many fingers can be used and where they can be placed on an object.

Intrinsic object properties are perceived primarily through vision or haptics, though some may be inferred from audition. During the planning phase, only visually perceived object properties are available, as noted in Chapter 4. These include the visual perception of object shape (Jeannerod, 1984; Klatzky & Lederman, 1987), volume or size (Klatzky & Lederman, 1987), and surface spatial density (Klatzky & Lederman, 1987). Humans seem to infer the location of the center of mass (Mason, 1986). After contact with the object, object properties can be perceived haptically, as discussed in Chapter 6. Using exploratory procedures, the human hand can extract surface roughness, temperature, and weight (Klatzky & Lederman, 1987). Using wielding, length, weight, moment of inertia and center of mass can be perceived (Hoisington, 1920; Solomon, Turvey, & Burton, 1989). Using holding and jiggling, weight can be perceived (Brodie & Ross, 1985; Victor Raj, Ingty & Devanandan, 1985). Neurally, Iwamura and Tanaka (1978) showed somatsensory cortical responses to differently shaped objects.

9.1.2 Tasks

Grasping occurs within the constraints of some task, e.g., grasping a screwdriver to turn a screw, grasping a screwdriver to lever open a can of paint. The functional requirements can be summarized as follows:

a) apply forces to match the anticipated forces in the task (stable grasp)

b) impart motion to the object (manipulate) or transport the object as necessary
c) gather sensory information about the state of the interaction with the object during the task in order to ensure grasping and manipulative stability

In the definition of prehension, the words 'functionally effective' are used to highlight the fact that the forces must be applied within the functional constraints of the task; i.e., while forces can be used to effect a stable grasp and impart motions as needed in a task, there are functionally specific demands on how this is accomplished, such as the precision requirements or stability needs.

Much work has gone into characterizing tasks, without much agreement even within fields. For example, roboticists have developed analytic measures, many of which are listed and explained in Chapter 6. These include compliance (Mussa-Ivaldi, 1986; Salisbury, 1985), connectivity (Salisbury, 1985), force and form closure (Nguyen, 1986a, Salisbury, 1985), grasp isotropy (Li & Sastry, 1990; Salisbury, 1985; Yoshikawa & Nagai, 1990), stability and resistance to slipping (Fearing, 1986; Nguyen, 1986b, 1987a). Yet, there isn't agreement which should be included in an objective function for choosing a grasp.

These analytic measures can be used as a start in being explicit about task requirements. In terms of the application of forces, there is a tradeoff between force and position control in response to perturbations. This is the issue of compliance. When choosing a prehensile posture, humans make assumptions about the external forces that could arise during the task. This is the issue of force closure. The degree to which these external forces must be counteracted is the issue of force and form closure, and it also refers to the issue of resistance to slipping. The direction and magnitude of the applied forces required in the task is the issue of internal forces. Whether forces have to be applied accurately is the issue of isotropy. Finally, stability refers to the needed response to perturbations. (See Fearing, 1986; Nguyen, 1986a,b, 1987a,b; Salisbury, 1985).

In terms of imparting motion, there is the question of how many degrees of freedom are needed. This is the issue of connectivity. Whether arbitrary motions must be imparted to the object is the issue of manipulability. A finer point is whether the motions have to be imparted accurately, and this is the issue of isotropy. (See Li & Sastry, 1990; Salisbury, 1985; Yoshikawa & Nagai, 1990).

Finally, in terms of gathering sensory information, there are analytic measures for the design of sensors. The sensivity required in a task deals with sensor spatial resolution, sensor spacing, and the sensitivity of the sensors. The required speed of response is a bandwidth issue. An important question relative to tasks is what information must be transduced (e.g., finger normal forces, tangential forces, contact, joint torques, vibrations changes in forces). (See Cutkosky & Howe, 1990; Fearing & Hollerbach 1985).

From the experimental literature, tasks are described at the level of 'move as quickly and as accurately as possible' or 'pick up the dowel.' At this level, an environmentally-defined goal is made explicit. Goals can be subdivided into sub-tasks occurring in serial order, and a task plan constructed that consists of desired subgoals without regard to the details of the actions necessary to accomplish them. Task plans have been constructed for robots (Lozano-Peréz & Winston, 1977) and as models for the CNS in terms of coordinated control programs (Arbib, 1985). Goals can be represented in terms of sensory consequences (Schmidt, 1975; Cole & Abbs 1987). Mismatches between the actual outcome and the anticipated sensory consequences cause reprogramming, but the error processing can also be incorporated into the plan, as modelled with TOTES (Miller, Galanter & Pribram, 1960).

In terms of human understanding of tasks, it is hard to relate these high level descriptions to the lower level analytic measures (Cutkosky, 1989). Yet, at the level of human performance, it is observable that postures are chosen with implicit knowledge of issues such as stability, resistance to slipping, force closure, connectivity, etc.

9.1.3 Hands

The human hand has both precision and power capabilities (Napier 1956). It also has a variety of ways to grasp objects. Prehensile postures present different degrees of available force, of available motion, and of available sensory information. From the variety of possible postures, the CNS matches the precision and power requirements of the task with the precision and power capabilities of the human (Napier, 1956). But there are constraints on the ways that the hand can be postured, as well as on the potential success of a chosen posture. Postures are created by the muscles of the hand directing the bones into some configuration, based on the motion capabilities of the various joints.

The definition of prehension stresses the fact that the human hand is both an input and output device. As an output device, it can apply forces both to match the anticipated forces in the task and to impart motion to the object as necessary. As an input device, it can gather sensory information about the state of the interaction with the object during the task in order to ensure grasping and manipulative stability. Like the eye, the sensory and motor functions of the hand are intertwined and indivisible -- as the hand is moving and feeling to grasp, it is grasping to feel and move objects. Covariance of cutaneous and articular motion provides information for haptic form perception (Gibson, 1962).

Sensorimotor features of the hand, as described in Chapter 6, include glabrous skin structure, eccrine glands, cutaneous mechanoreceptors, proprioceptors, muscles, tendons, and joints. In terms of the glabrous skin structure, properties include papillary ridges; ability to comply, hold and resist pressure and shearing forces; dermis and epidermis interface; fat pads; increase in stiffness to loads; elasticity; viscoelastic properties; and response to friction. (See Bowden & Tabor, 1967; Comaish & Bottoms, 1971; Eckert, 1989; Montagna & Parakkal, 1974; Moore, 1972; Quilliam, 1978; Wilkes, Brown & Wildnauer, 1973). In terms of the eccrine glands, properties include spacing, large number in palms, periodicity, discharge during gripping, mental responses, composition of sweat, efferent pathways, effect on coefficient of friction, and the mechanical effect on skin in terms of boundary lubrication creating adhesion. (See Gabella, 1976; Jones, 1989; Kuno, 1934; Moberg, 1962; Naylor, 1955; Rothman, 1954). In terms of the cutaneous mechanoreceptors, properties include quantity (they are numerous in the hand), morphology and location of receptors, organization of afferent terminals in spinal cord, receptive field size, receptor innvervation density, and adaptation characteristics. (See Johansson, 1978; Johansson & Vallbo, 1983; Vallbo & Johansson, 1984). In terms of proprioceptors, properties include morphology and location of receptors (in joints, muscles, and tendons), number, and response characteristics. (See Babu & Devanandan, 1991; Devanandan, Ghosh & John, 1983; Devanandan, Ghosh & Simoes, 1980; Sathian & Devanandan 1983). There is a lack of tendon organs in the hand. With a large number and density of muscle spindles in the hand, they seem to be implicated in perception of direction, distinct from the perception of movement. Digital joint mechanoreceptors are specialized particularly for detection of dynamic mechanical changes, rather than static joint position. The traditional view is that joint receptors respond to motion, while cutaneous receptors respond to contact. But recent evidence shows that the reverse is also true. The muscles (somatically innervated sensorimotor system) work in parallel with the eccrine sweat glands (autonomically innervated sudomotor system). Biomechanicians have measured aspects of hand postures, such as maximum grip strength, mechanical advantages of tendons, effect of wrist orientation, torques at the joints, and direction of frictional and shearing forces for various object sizes. See (Amis, 1987; Chao et al., 1989; Hazelton et al., 1975).

As described in Chapter 2, taxonomies of prehensile capabilities have been developed that offer insights into the complexity of human prehension. Across this diverse set, themes are repeated, suggesting the possibility of a unifying view. Hand surfaces, hand shapes, functions, and object characteristics are possible identifying features for taxonomies (Cutkosky, 1989; Jacobson & Sperling, 1976; Kamakura et al., 1980; Kapandji, 1982; Schlesinger, 1919; Taylor, 1948). Before actual tools were constructed, our hands were the tools, and prehensile postures can be described in those terms (Schlesinger, 1919). Power versus precision capabilities have been noted (Napier, 1956). Power grasps create a method for fixing the object in the hand, while precision grasping offers manipulative abilities by opposing the pads of the thumb and fingers (Landsmeer, 1962; Napier, 1956). The three jaw chuck (Schlesinger, 1919) and dynamic tripod (Elliott and Connolly, 1984; Kroemer, 1986), between the thumb, index, and middle fingers, are precision postures that allow fine manipulations. Other sensorimotor features of the hand are exhibited in the lateral pinch (Skerik et al., 1971), the hook grip (Napier, 1956), the adduction grasp (Kamakura et al., 1980), and the finger touch (Kroemer, 1956). This latter notion we call a 'finger-as-antenna', highlighting the hand's sensorimotor capabilities. Importantly, power and precision capabilities can be exhibited in one posture, as when tying knots (Napier, 1956).

In all these postures, the hand is applying forces to the object in three directions with respect to the palm. We call the participating hand surfaces grasping surface patches on virtual fingers. A virtual finger is the palm or else a collection of one or more real fingers. Pad opposition occurs between the finger and thumb pads along an axis generally parallel to the palm. Due to the nature of the sensorimotor features of the hand, it provides the ability to comply with small forces, impart small motions, and gather precise sensory information to match the manipulative requirements of the task. Palm opposition occurs between the fingers and palm along an axis generally perpendicular to the palm. It matches larger anticipated forces, gathers less precise sensory information, and only the arm and wrist are available to provide grosser motions. Side opposition is a compromise between these, a link or bridge between them. It occurs between the thumb pad (or ulnar side of fingers) and the radial side of the fingers along an axis generally transverse to the palm. This posture offers a medium range of forces while still offering some availability of sensory information due to the thumb pad being in contact with the object and also some ability to impart motions to the object (as in turning a key). Importantly, combinations of these three oppositions create postures that bring to bear the sensorimotor features of the hand in order to match the task requirements, exactly as Napier (1956) argued.

Besides the two virtual fingers used to create an opposition, a third virtual finger can be used to apply an opposition against a task related force or torque, as in holding a suitcase in a hook grip. A virtual finger three (VF3) can apply a force against gravity, can impart motion mostly with the arm or wrist, and can gather sensory information using sensors in the hand surfaces to determine the state of the object. Extending a finger (usually the index) as an antenna is an excellent way to enhance the availability of sensory information (due to the large number of mechanoreceptors in the finger pads and interphalangeal joints) and apply a force in a specific direction. Although it reduces the number of fingers available for applying forces, the extended finger in itself can apply a limited force, provide direction and impart some motion as necessary for a VF3. Importantly, it can be used in combined grasps, as seen in extending the index finger on a screwdriver or knife, or placing the thumb on the side of a beer mug.

The sensorimotor features of the hand integrate into <u>active touch</u> in order to extract object properties. Specific exploratory movements of the hand that have been studied include wielding (Hoisington, 1920; Solomon, Turvey, & Burton, 1989), jiggling (Brodie & Ross, 1985; Victor Raj, Ingty & Devanandan, 1985), holding, lateral motion, pressure, contact, enclosing, and contour following (Klatzky & Lederman, 1987). Human movements of this type have been observed to have a natural frequency of 1.56 Hz (Kunesch, Binkofski & Freund, 1989). But the sensorimotor features of the hand integrate into <u>active manipulation</u> using sensory information to monitor and guide motion. Manipulative actions, or performatory movements, of the fingers have been listed as: squeezing, twiddling, rolling, rocking, sliding, and stepping, while the dynamic tripod posture allows oscillations of the object (Elliott & Connolly, 1984). These movements occur along the same coordinate frame that oppositions do, as shown in Chapter 6. The natural frequency for manipulative movements, in humans, has been observed to be in the 4-7 Hz range (Kunesch, Binkofski & Freund, 1989).

9.1.4 Mapping between inputs and outputs

The act of grasping an object involves the planning, setting up, using, and releasing of an opposition space for the task, as outlined in Chapters 3 through 7.

During the planning phase, task-related object properties are perceived, as noted above. This entails seeing an opposition vector in the object that will satisfy the required degrees of freedom of the task. It depends on previous knowledge about the behavior of objects, and our ability to predict and anticipate task-specific prehensile occurrences. A grasp strategy is chosen, selecting appropriate opposition types, mapping virtual fingers into real anatomical fingers, and determining opposition space parameters. The choice of the opposition vector must satisfy the constraints imposed by the object, task, and hand. Computational models have demonstrated possible ways to map object and task characteristics to hand postures, using expert systems (Cutkosky & Howe, 1990; Iberall et al., 1988; Stansfield, 1991) and neural networks (Iberall, 1988; Uno et al., 1993). Finally, a location and orientation in space for the hand to go to must be planned. Planning a hand location and orientation will depend on the grasp strategy chosen. Such a decision can be based on retinal information (Klatzky et al., 1987, Sivak & Mackenzie, 1992) or on knowledge about the hand. As was shown in Chapters 4 and 5, cortical parietal areas, premotor and motor areas, and spinal areas are all processing information relevant to arm reaching and grasping (Alstermark, Gorska, Lundberg, & Pettersson, 1990; Georgopoulos 1990). For example, Georgopoulos (1990) shows evidence of motor cortex and area 5 computing a Populational Vector that specifies the direction of arm movement prior to movement.

Setting up the opposition space involves preshaping the hand and transporting it towards the object. At first, the hand moves in an unrestrained way opening to a posture suitable for the task (Jeannerod, 1984) and to stretch the finger flexors (Smith et al., 1983). The relationship between the transport and grasping components appears to be functionally specific to the high level goal of the task (Jeannerod, 1984; Marteniuk et al., 1987; Wing, Turton, & Fraser, 1986). Noting the interwoven action of wrist, forearm, elbow, and shoulder muscles, we suggest that the palm is the likely interface between the transport and shaping components. Once the hand is preshaped and the palm transported to a place near the object, a guarded enclosing motion occurs, trying to establish tactile contact with the object. Sensory information is sought, comparing the anticipated tactile feedback to the current tactile information. The arm is subservient to the hand, helping in the guarded move to establish contact. The force-generating muscles become active to 'close the fingers' around the object. During this setting up process, the CNS may be trying to get some parameters into the 'right ballpark' which can then be fine tuned (Arbib, Iberall, & Lyons, 1985; Greene, 1972; Iberall, 1987a).

During the use of opposition space, several subphases have been noted (Johansson & Westling, 1988b; MacKenzie, 1992; Westling & Johansson, 1987; Weir, 1991; Weir & MacKenzie, 1993). Capturing the object involves compliant motion against the object. Lifting the object involves a differential response by the normal component of the active force and gravitational component (Johansson & Westling, 1988b; Westling & Johansson, 1987; Weir, 1991; Weir & MacKenzie, 1993; Winstein, Abbs & Petashnick, 1991). If the active forces are of insufficient magnitude, microslips from the cutaneous receptors will signal motor adjustments to be made. This pressure must be maintained during the lifting, holding, manipulating, and replacing of the object.

For example, if the task goal is to 'move as quickly and as accurately as possible,' timing parameters are chosen consistent with Fitts' Law while also consistent with kinematic and dynamic constraints acting on the hand and arm. Not only must the anticipated forces be matched, an opposition space must be chosen that allows perceptual systems access to the sensory information consistent with the accuracy requirements of the task. Accuracy suggests pad opposition, but only if the forces are not too great. With greater forces, one compromise is to use more fingers in the VF opposing the thumb. Of course, anatomical constraints limit the number of ways real fingers can be mapped into VFs.

The words 'functionally effective' are used to highlight the fact that the forces must be applied within the functional constraints of the task; i.e., while forces can be used to effect a stable grasp and impart motions as needed in a task, there are functionally specific demands on how this is accomplished. In a functional sense, grip and load forces are applied by virtual fingers so that the object is not dropped and so that the object is not crushed. (See Johansson & Westling, 1990; Johansson & Westling, 1984; Westling, 1986; Westling & Johansson, 1984; Winstein, Abbs & Petashnick, 1991). Prehensile behaviors demonstrate mechanisms that help prevent errors from occurring, especially when there is uncertainty; this includes opening the the thumb and finger to a wider aperture during the Setting up of the Opposition Space under uncertainty (Wing et al., 1986) and safety margins during Using the Opposition Space (Johansson & Westling, 1990). Mechanisms have been noted that help maintain the grasp: magnet phenomenon (Johansson & Westling, 1990), eccrine secretion enhancing adhesion (Cutkosky & Howe, 1990), vibrations against the skin exciting cutaneous mechanoreceptors (Torebjörk, Hagbarth & Eklund, 1978).

Ultimately, the versatility of the human hand stems from what Napier pointed out in 1956, that precision and power are not mutually exclusive. The human hand (and brain!) can resolve these multiple task components and in doing so, find a set of oppositional forces that are functionally effective for satisfying the competing task requirements for arbitrary objects. This is true, whether the task is to hold one or even 10 oddly-shaped objects at a time, to do either one or many things with them! The human hand has a variety of ways to grasp objects stably; the decision that the CNS must make in choosing which oppositions to use depends on balancing the functional requirements of the task with the functional abilities of the hand and body.

9.2 Phases of Prehension Revisited

One of the key points of this text has been that prehensile behavior unfolds over time, as introduced in Chapter 3, detailed in Chapters 4 through 6 and summarized in Chapter 7. Recalling Figure 7.1, we note the four main phases of prehension, planning, setting up, using, and releasing an opposition space. In Chapter 8 it was suggested that there are also levels of analysis for understanding prehension. High level goals (from the opposition space level) travel downward to the Biomechanical level and Sensorimotor level. In turn, from these levels, constraints work upwards. Sources of these constraints come from evolution, anatomy, biomechanics, functionality, and motivations.

A model is presented in Figure 9.2 that combines these two perspectives. Starting from a resting posture during the Planning of an Opposition Space, the hand opens during the Setting up of the Opposition Space. Once opened, it can enclose around the object. On contact, the Using of the Opposition Space occurs. Finally, the

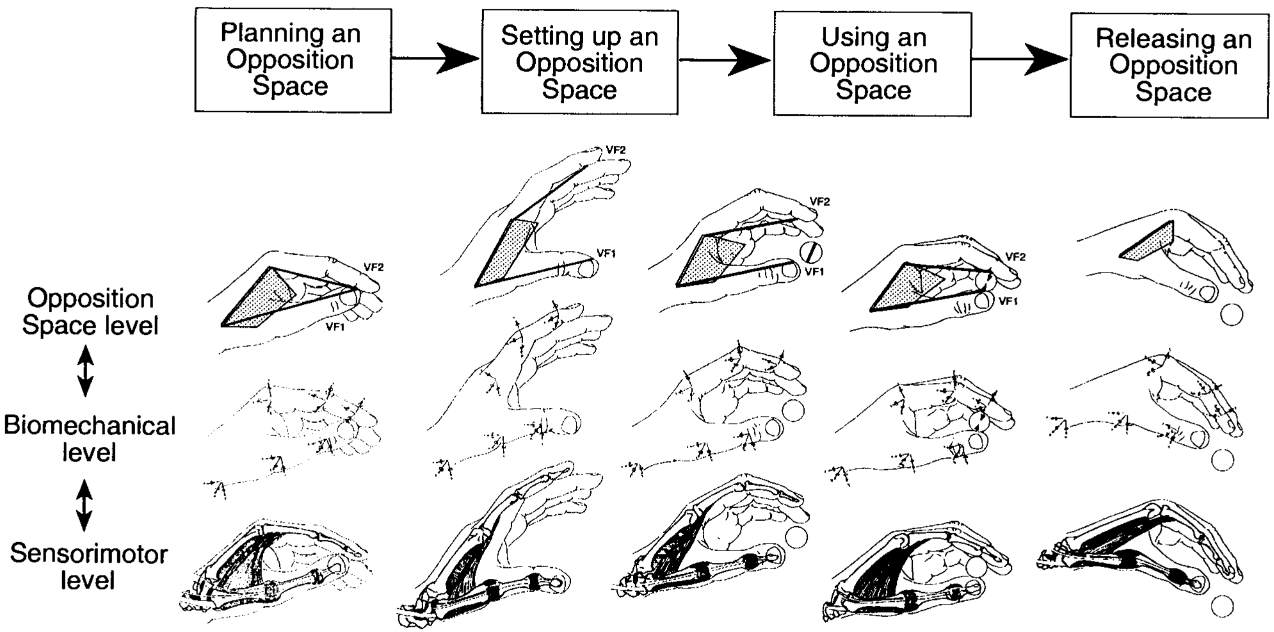

Figure 9.2 Starting from a resting posture during the Planning of an Opposition Space, the hand opens and prepares for contact during the phase of Setting up of an Opposition Space. Once contact is made, Using an Opposition Space begins. Finally, the opposition space is released. Motor commands from the nervous system are generated at the Opposition Space level, the Biomechanical level, and the Sensorimotor level, and movement occurs satisfying all the constraints acting on the system.

posture is released during the Releasing Opposition Space, and the hand comes back to a position of rest.

In order to effect these phases and this prehensile unfolding, motor commands from the nervous system are generated at all three levels: the Opposition Space level, the Biomechanical level, and the Sensorimotor level. The environmental goal, along with the subgoals for each phase filter downward. Movement over the phases occurs satisfying the constraints acting at the various levels. One of the key planning parameters, we are suggesting, is the palm, as an interface between the grasping component and the transport component, as viewed over the last decade.

During the Planning of an Opposition Space, mental activities perceive task-specific object properties, select a grasp strategy, and plan a hand location and orientation. An opposition vector is seen in the object. At the Biomechanical level, the perceived frictional state and required forces are constraining the selection of an opposition space. The posture must fit within the biomechanical constraints acting on the hand and muscles chosen to effect that posture. At the Sensorimotor level, there are further constraints dealing with the requirements for sensory information and fine motor control. For example, efficient use of the sensorimotor features of the hand is a potential constraint. Motivational and functional goals are part of the context within which these choices are made.

While Setting Up an Opposition Space, the palm is positioned and oriented with respect to the opposition vector perceived in the object. Biomechanical constraints on the extrinsic hand muscles as they cross the wrist affect the chosen arm configuration. Certain wrist angles, depending on the oppositions chosen, afford a mechanical advantage, and therefore, the more proximal joints must be configured. In parallel, the fingers open into the chosen posture. After peak aperture and when the palm has been positioned and oriented, the fingers start a guarded movement in order to capture the object. Task-specific circuits await sensory information as the palm is transported closer to the object and fingers enclose. The muscles that will supply the forces needed in the task become active.

During Using of an Opposition Space, grip and load forces first increase differentially and then stabilize to provide the active forces necessary in the task. Sensorimotor features of the hand, such as the sensitivity of mechanoreceptors and the strength of muscles, are used to perform the task.

9.3 Future Directions

Returning to the triangle strategy introduced in Chapter 1 (see Figure 9.5), a full circle is made to show the methods with which computational and experimental modelling can help understand the brain and the hand. For example, computational models have provided methods through which it is possible to compute ill-posed problems such as the inverse kinematics and inverse dynamics problems for end point trajectory formation. These models made explicit issues such as the coordinate frame for the movements, use of constraints, control parameters, speed of the computation, and use of sensory information. Experimentalists should be looking for information processing within specified coordinate frames, as was seen in Georgopoulos et al. (1988) and Soechting and Flanders (1991). While it is evident from the anatomy why a palm-focused model is reasonable for prehension, more experimental evidence is needed.

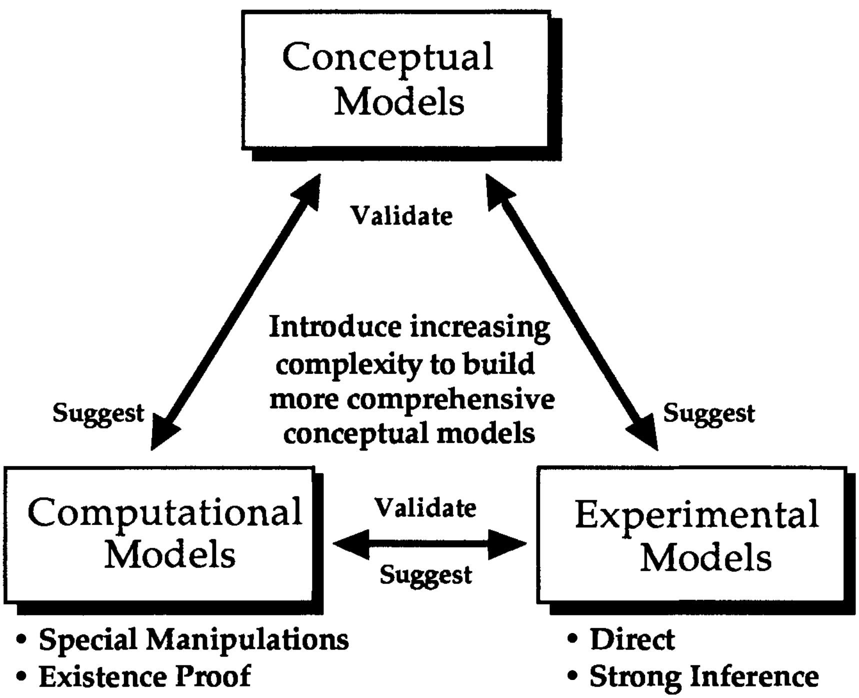

Figure 9.3 The triangle strategy involving conceptual models, experimental models and computational models.

Experiments also suggest computational models. Effective experiments have included perturbation studies, where microslips or externally imposed changes in object properties are observed. Models are needed for a better understanding of the methods in which the computations may be performed. Analytic models of friction, and levels of asperities in the contacting surfaces are needed, as are computational models of force generation by the muscle, skin, and 'passive' viscoelastic properties of the hand. The weighting and calibration of information across receptor types and sensory systems is needed to understand better how exteroceptive and proprioceptive systems are integrated with descending motor commands.

Computational and experimental models show the methods by which feedback and feedforward control can work, depending on the success of anticipatory movements. The role of practice and past experience needs to be modelled for better understanding the role of feedforward processes. If unexpected perturbations occur, feedback control can make fine adjustments. At which levels feedforward and fine adjustments can be implemented need to be defined more clearly.

Making explicit the influence of various constraints on the environment/performer, the need for a common vocabulary between experimentalists and roboticists is paramount. Much can be gained through increased sharing and communication, using a triangular approach to science.

This book is not comprehensive; many topics were left untouched. Handedness, asymmetries (in hand and brain) and bimanual activities (splitting the task demands) are glaring in their omission. Illusions like the size-weight illusion were only alluded to. Postural (trunk, hip, and lower limb) involvements were excluded from consideration, as were parallels between locomotion and limb control. Little was said about central and peripheral fatigue, and corresponding adaptations. Detailed treatment of the research on special populations has been left out. These include individuals with sensory or neurological dysfunction, such as blindness, and patients with brain lesions (e.g., apraxia, optic and motor ataxia). The effects of other diseases (such as arthritis), conditions (like congenital anhydrosis) and injuries (dislocations, carpal tunnel syndrome) on hand function, are also notably absent.

It is our goal that this text be relevant to workers in the applied sciences. There is much relevance here to human factors applications. This includes the design of human-computer interfaces, other human-machine interfaces (e.g., automobile control panels), hand tools, and remote manipulators. For computer graphics, there are issues for scientific visualization and human hand animation. The role of vision and haptics will be critical for applications to virtual reality. For engineers, challenges exist for telerobotics and telemanipulation. For the medical professions, understanding the normal hand is relevant for applications to rehabilitation, surgery and microsurgery, functional electrical stimulation, hand therapy, and prosthetics.

9.4 Summary

What do hands do? The human hand interacts with the world in complex ways. When an object is grasped, it is not only grasped for itself; it is grasped for a reason. A person grasps an object to do something with it. Because we generally use our one dominant hand to perform this task with this given object, we feel that our hands and arms are always doing the same thing--reaching to grasp the object. However, the data explored in this book show that, depending on the task and object, there seem to be different control mechanisms. For pointing, which is a task performed in free space and basically with our arm, one controller is used. For grasping a pen to write with it, which is an oscillatory task that involves first a free space movement and then the grasp, lift, and oscillations, another controller is used. For grasping the pen to hand it to someone, a third controller is used. It is, as Greene (1972) said, as if we had a collection of virtual arms.

Our brains are complex systems, containing many redundancies. While the motoneurons are final common pathways on the way to our hands, many parallel systems are involved in selecting the right combination of control strategies to allow us to perform sophisticated, versatile, goal-directed behaviors. Evolutionary specializations have enhanced the human hand's ability (through control by the CNS) to perform a wide variety of prehensile tasks, equipping the hand as both a precision and power device. Within the complex interaction of physical constraints, active and passive sensorimotor features, goals and motivations, prehensile postures are chosen that will apply functionally effective forces to an object. The term 'functionally effective' is used in order to make explicit the notion of task goals (i.e., applying forces, imparting motions, gathering sensory information), creating constraints on the methods by which a human hand is shaped into a force-applying and sensory-gathering posture.

The opposition space model focuses on human hand functionality in terms of task requirements and explicit parameters. By comparing hand functionality and task requirements, the effectiveness of a posture can be determined for a given task. The model avoids the symbolic descriptions of prehensile postures. By separating anatomy from function, it provides a way to study the complexity of motor control, as well as suggests ways to design and control versatile dextrous robot hands. Coming full circle, once better mechanical hands are designed, that closely resemble human hands in terms of performance, the next step is to replace the dysfunctional hand with a versatile prosthetic device. Remembering the triangle strategy, the CNS can be viewed as the central nervous system controlling human hands or as the computational nervous system controlling robot or prosthetic hands.

The potential ways that the hand can generate opposing forces must be balanced with the acquisition of sensory information in order to accomplish the key aspects of the task (control, affixment, and dextrous manipulation). It is this balance that teleologically gives rise to the posture observed at any time. The posture emerges within a constraint space in which all the constraints of the task must be satisfied. In summary, detailed examination of the phases of prehension provides a start towards an explicit vocabulary for prehension, bringing together current knowledge from behavioral, biological, and analytic disciplines into a common framework.

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APPENDICES

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Appendix A. Human Upper Limb Anatomy

"...Nature has admirably contrived the actual shape of the hand so as to fit in with this arrangement. It is not all of one piece, but it branches into several pieces; which gives the possibility of its coming together into one solid piece, whereas the reverse order of evernts would be impossible. Also, it is possible to use the pieces singly, or two at a time, or in various ways. Again, the joints of the fingers are well constructed for taking hold of things and for exerting pressure."

--Aristotle, Parts of Animals, IV, X.

In this appendix, we summarize information relevant for following terminology used in the text. We consider the entire upper limb, including the shoulder girdle, since moving the human hand to different spatial locations requires these structures. For more detailed information, we refer the reader to excellent anatomy references. Our primary sources for this information included Basmajian (1970), Tubiana (1981), Hollinshead (1982), and Ranney and Grainger (1987).

A.1 Planes of the Body, Terms for Direction

For clarity, anatomists use a standard anatomical position for descriptive accounts of the human body, regardless of its position and orientation. In anatomical position, the body is standing erect, with the face and eyes looking straight ahead, feet together, arms by the sides with the palms facing forwards.

Figure A.1 shows the planes of the body, defined in anatomical position. The sagittal plane is any vertical plane which divides the body into right and left halves. The median sagittal plane divides the body into right and left halves at the body midline. The frontal or coronal plane is any vertical plane dividing the body into anterior and posterior portions. The horizontal or transverse plane divides the body into upper and lower parts.

Directional terms explain exactly where a structure is located on the body. The following terms are used in the text wherever possible, for clarity of communication.

Anterior (ventral): nearer to or at the front of the body; "in front of"
Posterior (dorsal): nearer to or at the back of the body; "behind"
Superior (cephalic): toward the head or upper part of a structure; "above"
Inferior (caudal): away from the head or toward the lower part of a structure; "below"
Medial: toward the midline of the body
Lateral: away from the midline of the body
Proximal: near or closer to the trunk
Distal: far or farther from the trunk
Superficial: toward or on the surface of the body
Deep: away from or beneath the surface of the body

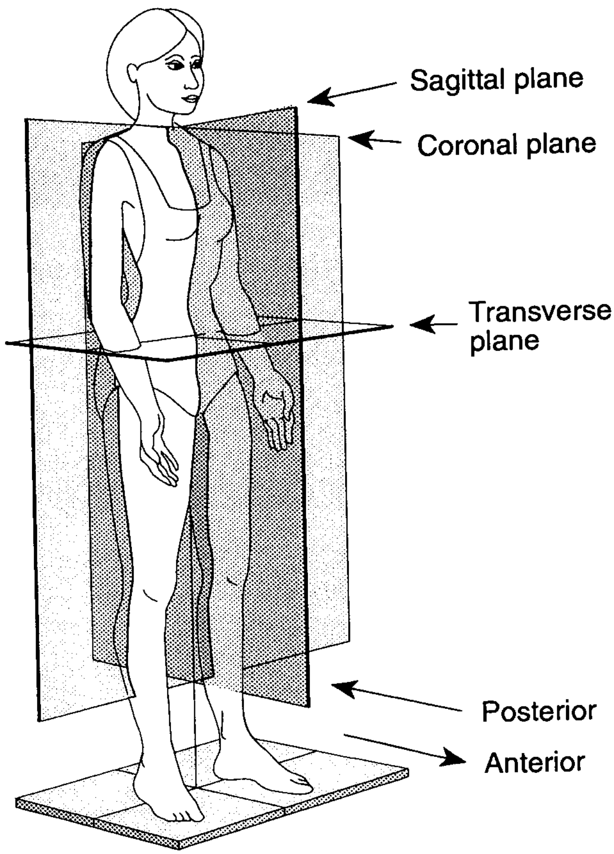

Figure A.1 Planes of the body. See text for details.

A.2 Skeletal Structure of the Upper Limb

The upper limb skeleton is suspended by muscles to allow for mobility. Its only skeletal connection with the axial skeleton (in the trunk) is at the body midline, through the clavicle. The clavicle articulates with the sternum at its medial, more movable end, and with the scapula, a free moving structure at its lateral end. Interestingly, the clavicle is the first bone in the human body to commence ossification (in about the 5th embryonic week) and among the last bones in the body for secondary ossifications to be completed (by about 20 - 25 years of age, Camp & Cilley, 1931, cited by Hollinshead, 1982).

Figure A.2 shows the bones and joints of the upper limb skeleton. The arm consists of the humerus that articulates proximally at the shoulder with the glenoid fossa of the scapula and distally with the radius and ulna in the forearm. The hand itself consists of eight carpal bones, five metacarpals, two phalanges in the thumb, and three phalanges in each of the four fingers. Figure A.3 provides labels for the bones and joints in the hand.

A.3 Movement and Degrees of Freedom of Joints in the Upper Limb

Movement terms are are provided for consistent descriptions of movements of body segments. The following terms are used to describe motions in the upper limb. Figure A.4 shows some of these limb movements.

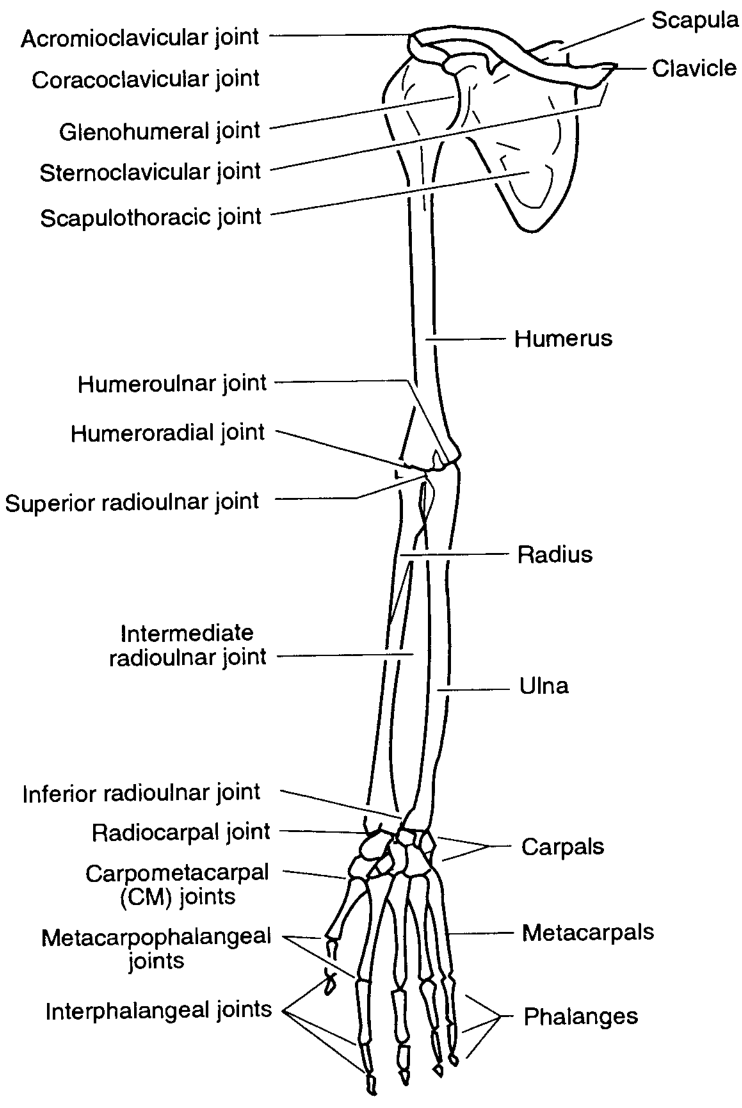

Figure A.2 The bones and joints of the upper limb skeleton. Two bones, the radius and ulna, make up the forearm, while the arm (commonly labelled the upper arm) consists of the humerus. The scapula and clavicle are in the shoulder, with the clavicle attaching to the sternum at the body midline. The right upper limb is shown in anatomical position with the palm facing forward.

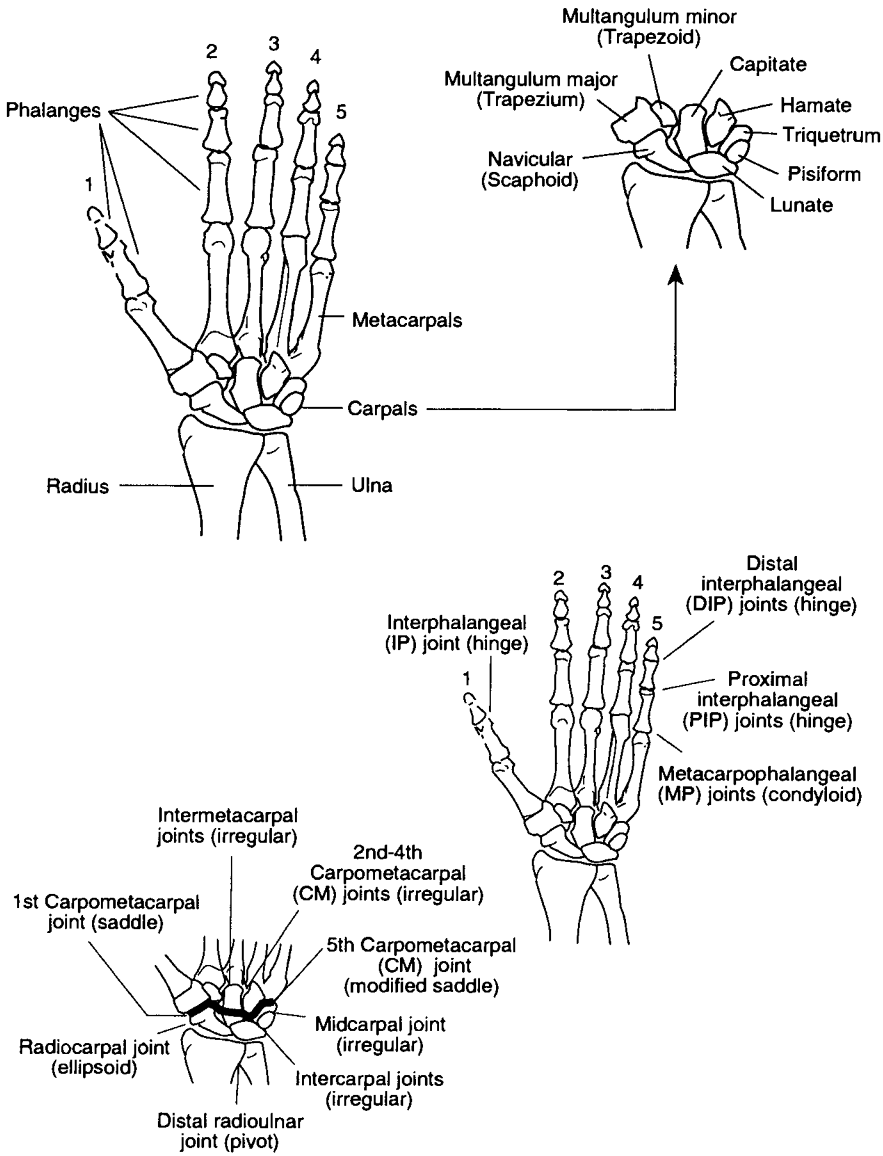

Figure A.3 **The bones and joints of the hand and wrist. The palm contains five metacarpals bones, while each finger has three phalanges, with the thumb only having two. The wrist consists of eight small bones. The joints between the bones allow movement, according to the shape of the articulating surfaces, e.g., heads of the bones. The types of joints and motions are described in Table A.1.**

Table A.1 Degrees of freedom (df) of the upper limb

Bones	Joints (type)	df	Motions
Pectoral Girdle-Shoulder			
Clavicle	sternoclavicular (plane, synovial)	3	protraction & retraction elevation & depression upward & downward rotation
Scapula (free& mobile)	acromioclavicular (plane, synovial) coracoclavicular (ligament, fibrous)	3	
	scapulothoracic (functional, fibrous, not a "true" joint)	3	NOTE: interdependent motions about all pectoral girdle joints, for total of 3 df
Shoulder-Arm			
humerus	glenohumeral (ball and socket, synovial)	3	abduction & adduction flexion & extension internal & external rotation NOTE: when arm is above shoulder height, there is also motion about pectoral girdle joints
Elbow-Forearm			
ulna	humeroulnar (modified hinge, synovial)	2	flexion & extension ulnar abduction & adduction
radius	humeroradial (pivotal, synovial)		same as humeroulnar for flexion & extension and same as superior radioulnar in supination & pronation
	superior radioulnar joint (pivotal, synovial)		
	intermediate radioulnar joint (interosseus membrane, fibrous)	1	the 3 radioulnar joints provide for rotation of the radius about the ulna in pronation & supination
	inferior radioulnar joint (pivotal, synovial)		

Table A.1 Degrees of freedom (df) of the upper limb (continued)

Bones	Joints (type)	df	Motions
Wrist & Hand			
scaphoid, lunate & triquetrum (3 carpals)	radiocarpal (ellipsoid, synovial)	2	flexion & extension radial & ulnar deviation (abduction & adduction)
carpals	midcarpal joint & intercarpal joints (irregular, many planar, synovial joints)	1 2-3?	flexion & extension radial & ulnar deviation rotations? NOTE: there are inter-dependent motions about the radiocarpal, midcarpal & intercarpal joints
meta-carpals	1st carpometacarpal (saddle, synovial)	3	flexion & extension abduction & adduction internal & external rotation NOTE: rotation is coupled to flexion & extension (due to ligaments)
	2nd & 3rd carpo-metacarpal joints (irregular, synovial)	little	
	4th carpometacarpal (irregular, synovial)	1	flexion & extension
	5th carpometacarpal (modified saddle, synovial)	2?	flexion & extension abduction & adduction
	4th and 5th (+other) intermetacarpals (? , synovial)	1?	NOTE: with 5th mp abd? or cupping?

Table A.1 Degrees of freedom (df) of the upper limb (continued)

Bones	Joints (type)	df	Motions
Fingers			
phalanges	1st metacarpophalangeal (condyloid, synovial)	2	flexion & extension abduction & adduction
	2nd-5th metacarpophalangeal (condyloid, synovial)	2+	flexion & extension abduction & adduction NOTE: possible only in extension slight rotation
	1st interphalangeal (hinge, synovial)	1	flexion & extension
	2nd-5th proximal interphalangeal (hinge, synovial)	1	flexion & extension NOTE: there is coupling on extension of fingers 3 and 4 and individual differences in the independence of finger 5
	2nd-5th distal interphalangeal (hinge, synovial)	1	flexion and extension NOTE: there is limited independence of fingers 3, 4 and 5, with large individual differences

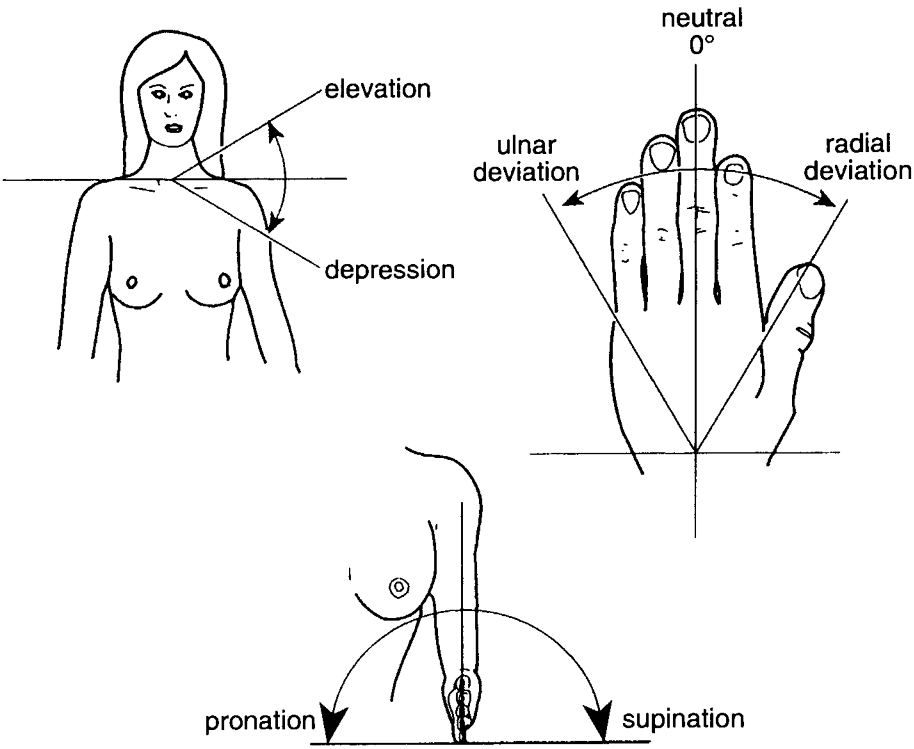

Figure A.4 Descriptions of movement. Shows elevation and depression of the shoulder, pronation and supination of the forearm, ulnar and radial deviation of the wrist. See text for details. Motions about all joints of the upper limb are summarized in Table A.1.

Flexion: to bend or to make a decreased angle
Extension: to straighten or to make an increased angle
Adduction: to move in the frontal plane towards (ad) the body midline; for the fingers, movement is toward the middle finger; for the thumb, movement in the sagittal plane toward the palm
Abduction: to move in the frontal plane away from (ab) the body midline; for the fingers, movement is away from the middle finger; for the thumb, movement in the sagittal plane away from the palm
Ulnar deviation: adduction at the wrist; movement of the little finger side of the hand toward the ulna of the forearm
Radial deviation: abduction at the wrist; movement of the thumb side of the hand toward the radius of the forearm
Horizontal adduction (Horizontal flexion): movement of the upper limb in the horizontal plane (forward) toward the midline of the body
Horizontal abduction (Horizontal extension): movement of the upper limb in the horizontal plane (outward) from the midline of the body
Elevation: to move the shoulder girdle superiorly
Depression: to move the shoulder girdle inferiorly
Rotation upward: rotation of the scapula around the sagittal axis, bringing the glenoid fossa upward and the inferior angle laterally
Rotation downward: rotation of the scapula around the sagittal axis, bringing the glenoid fossa downwardward and the inferior angle medially
Protraction: is movement of the shoulder girdle forward
Retraction: is movement of the shoulder girdle backward
Medial (internal) rotation: rotation around the long axis so the anterior aspect faces toward the midline
Lateral (external) rotation: rotation around the long axis so the anterior aspect faces away from the midline
Pronation: to turn the forearm so the palm faces posteriorly; medial rotation of forearm
Supination: to turn the forearm so the palm faces anteriorly; lateral rotation of the forearm
Circumduction: movement of a segement so that its free end traces a circle in space; the segment describes a cone whose apex is the attached end of the segment; a sequential combination of flexion, abduction, extension and adduction
Opposition: a special motion in which the thumb touches the tip of a finger; a composite of circumduction and flexion of the thumb

Based on the articulating surfaces, the types of joints allow for differing degrees of freedom of motion. For example a hinge joint in the elbow allows for one degree of freedom, whereas a ball and socket joint in the shoulder allows for three degrees of freedom. There are close to forty degrees of freedom in the upper limb, of which thirty or more are in the wrist and hand. These motions have standard anatomical labels, described above. The bones, joints, degrees of freedom and motions about the joints are summarized in Table A.1.

A.4 Muscles of the Upper Limb

Motion about a joint is caused primarily by muscle contractions (and in some instances, allowed by ligaments). There are about 58 muscles of the upper limb, and 9 may be considered as extrinsic to the upper limb, since they attach on other than limb skeletal parts. The rest are intrinsic to the upper limb, with attachments on the limb skeleton. Note that the extrinsic hand muscles cross the wrist and elbow, causing some motion at these joints as well as the joints in the hand. These are to be distinguished from the 19 intrinsic hand muscles, which do not cross the wrist joint. Table A.2 lists the upper limb muscles, and the number of joints crossed on the same line as their PRIMARY actions. Included are muscles which also have some action at more proximal joints than the primary action.

A.5 Peripheral and Segmental Innervation of Muscles of the Upper Limb

Table A.3 lists the upper limb muscles, their peripheral and segmental innervation.

A.6 Sensations of the Upper Limb, and Spinal Innervation

In Chapter 6, we consider cutaneous mechanoreceptors. Cutaneous sensations are relayed to the spinal cord via dorsal root ganglia at each segmental level. A dermatome is an area of skin innervated by a single dorsal root. Figure A.5 shows the segmental dermatome mapping of the upper limb, after Keegan et al. (1948), adapted from Hollinshead (1982). The upper limb innervation is derived primarily from C3 to C8 and T1. Dermatome boundaries are not as clear-cut as indicated below because more than one peripheral nerve sends afferents to each dorsal root, and fibers from serveral dorsal roots mix in the peripheral nerves.

Table A.2 Joints and muscles in the upper limb

Joints	Muscles: elev	depr	rotu	rotd	prot	retr	# joints crossed
Pectoral Girdle	**elev**	**depr**	**rotu**	**rotd**	**prot**	**retr**	
sternoclavicular	trapezius (upper)						3
acromioclavicular	levator scapulae						3
coracoclavicular	serratus anterior(upper fibers)						3
		pectoralis major					4
		latissimus dorsi					4
		pectoralis minor					3
		subclavius					3
			trapezius (upper and lower)				
			serratus anterior				
				levator scapulae			
				rhomboids			3
				pectoralis major			
				latissimus dorsi			
				pectoralis minor			
				serratus anterior			
					levator scapulae		
					pectoralis major		
					pectoralis minor		
						trapezius	
						rhomboids	
						latissimus dorsi	

where:

elev **elevation**
depr **depression**
rotu **rotation upward**
rotd **rotation downward**
prot **protraction**
retr **retraction**

Table A.2 Joints and muscles in the upper limb (continued)

Joints	Muscles						# joints crossed
Shoulder and Arm	**flex**	**ext**	**abd**	**add**	**intr**	**extr**	
glenohumeral	pectoralis major(clavicular head)						
	deltoid (anterior fibers)						1
	coracobrachialis						1
	biceps						3
	supraspinatus						1
		latissimus dorsi					
		teres major					1
		pectoralis major (sternal head)					
		deltoid (posterior fibers)					1
		triceps (long head)					
			deltoid (middle fibers)				1
			supraspinatus				
			biceps (long head)				
				pectoralis major (2 heads)			
				latissimus dorsi			
				teres major			
				coracobrachialis			
				triceps (long head)			
				deltoid (posterior fibers)			
					pectoralis major (2 heads)		
					latissimus dorsi		
					teres major		
					subscapularis		1
					deltoid (anterior fibers)		
						infraspinatus	1
						teres minor	1
						deltoid (post. fibers)	

where:

flex **flexion**
ext **extension**
abd **abduction**
add **adduction**
intr **internal rotation**
extr **external rotation**

Table A.2 Joints and muscles in the upper limb (continued)

Joints	Muscles: flex	ext	ulab	ulad	pron	supn	# joints crossed
Elbow and Forearm							
humeroulnar	brachialis						1
humeroradial	biceps						3
	brachioradialis						2
	pronator teres						2
		triceps					2
		anconeus					
			anconeus				1
				?			
superior r-u joint					pronator teres		
intermediate r-u joint					pronator quadratus		1
inferior r-u joint					flexor carpi radialis		
						supinator	2
						biceps	
						abd. pollicis longus	
						ext. pollicis longus	

Joints	Muscles: flex	ext	radv	ulndv	opp	# joints crossed
Wrist and Palm						
radiocarpal	flexor carpi radialis					5
midcarpal	flexor carpi ulnaris					3
carpometacarpal	palmaris longus					5
	abductor pollicis longus					
		extensor carpi radialis longus				5
		extensor carpi radialis brevis				5
		extensor carpi ulnaris				5
			extensor carpi radialis longus			
			extensor carpi radialis brevis			
			abductor pollicis longus			
			flexor carpi radialis			
				extensor carpi ulnaris		
				flexor carpi ulnaris		
					opponens digiti minimi	1

where:

flex	**flexion**	**ulab**	**ulnar abduction**
ext	**extension**	**ulad**	**ulnar adduction**
radv	**radial deviation (abduction)**	**pron**	**pronation**
ulndv	**ulnar deviation (adduction)**	**supn**	**supination**
opp	**opposition**		

Table A.2 Joints and muscles in the upper limb (continued)

Joints	Muscles: flex	ext	abd	add	# joints crossed
Fingers (excluding thumb)	**flex**	**ext**	**abd**	**add**	
metacarpo-phalangeal	interossei				1
	lumbricals				1
	flexor digiti minimi brevis (5)				2
	flexor digitorum profundus (2,3,4,5)				
	flexor digitorum superficialis (2,3,4,5)				
		extensor digitorum (2,3,4,5)			6
		extensor digiti minimi (5)			
		extensor indicis (2)			
			dorsal interossei (2,3,4)		1
			abductor digiti minimi (5)		3
			extensor digiti minimi (5)		
				palmar interossei (2,4,5)	1
proximal interphalangeal (PIP)	flexor digitorum superficialis (2,3,4,5)				7
	flexor digitorum profundus				
		interossei			
		lumbricals (2,3,4,5)			1
		extensor digitorum?			7
		extensor indicis (2)?			
		extensor digiti minimi (5)?			
distal interphalangeal (DIP)	flexor digitorum profundus (2,3,4,5)				7
		extensor digitorum?			8
		extensor indicis (2)?			7
		extensor digiti minimi (5)?			8
		lumbricals			
		interossei			

NOTE: The lumbricals have their origin on the 4 flexor profundus tendons on the palm; the interossei originate from the metacarpals. Both these intrinsic hand muscles join with the <u>extensor tendons on the proximal phalanges, thus affecting interphalangeal joints as well.</u>

where:

flex	**flexion**
ext	**extension**
abd	**abduction**
add	**adduction**

Table A.2 Joints and muscles in the upper limb (continued)

Joints	Muscles							# joints crossed
Thumb	**flex**	**ext**	**abd**	**add**	**intr**	**extr**	**opp**	
carpometacarpal	flexor pollicis brevis							
		abductor pollicis longus						
		extensor pollicis brevis						
		extensor pollicis longus						
			abductor pollicis longus					4
			abductor pollicis brevis					
				adductor pollicis				2
				1st dorsal interosseus				
							opponens	1
metacarpo-phalangeal	flexor pollicis longus							
	flexor pollicis brevis							2
	abductor pollicis brevis							
		extensor pollicis brevis						5
		extensor pollicis longus						
			abductor pollicis brevis					3
interphalangeal	flexor pollicis longus							6
		extensor pollicis longus						6

where:

flex	**flexion**
ext	**extension**
abd	**abduction**
add	**adduction**
intr	**internal rotation**
extr	**external rotation**
opp	**opposition**

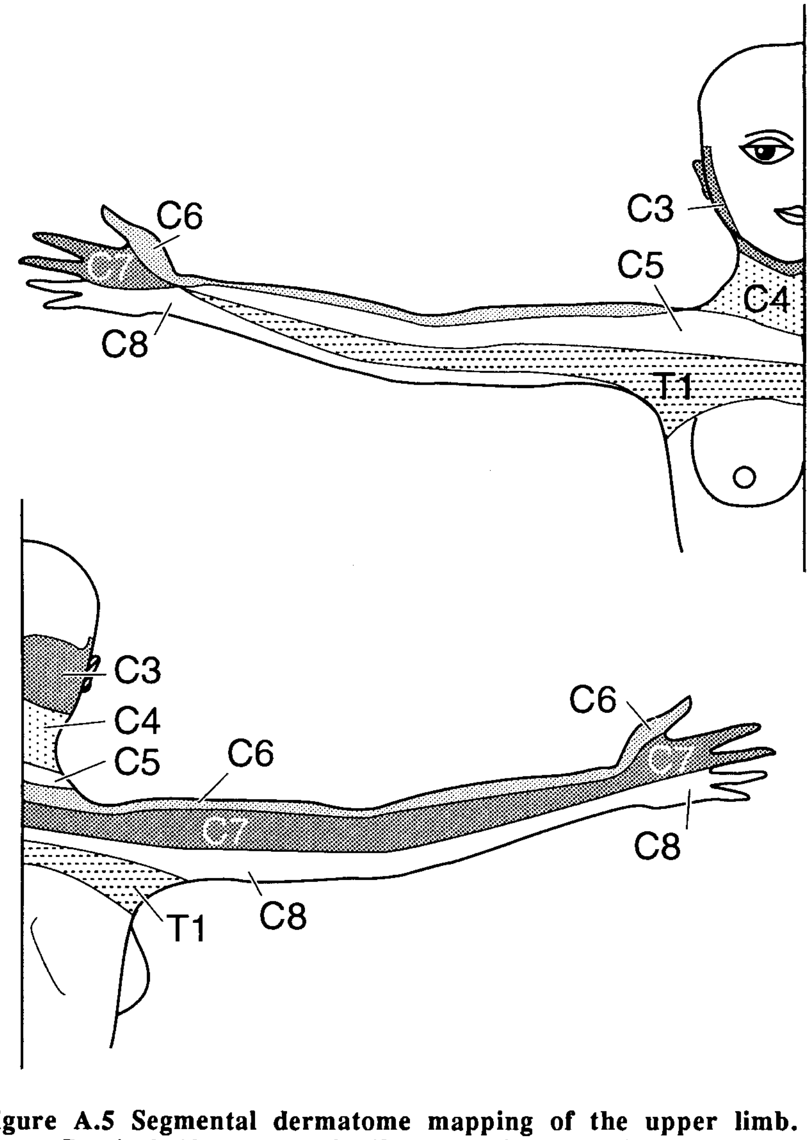

Figure A.5 Segmental dermatome mapping of the upper limb. C = Cervical, T = Thoracic (from Hollinshead, 1982; adapted by permission).

Table A.3 Innervation of muscles of the upper limb (from Hollinshead, 1982; adapted by permission)

MUSCLE GROUP	MUSCLE	PERIPHERAL NERVE	SEGMENTAL NERVE*
Extrinsic of shoulder	Pectoralis major	Med. and lat. pectorals	C5 - T1
	Pectoralis minor	Medial pectoral	C8
	Subclavius	N. to subclavius	C5, C6
	Serratus anterior	Long thoracic	C5 - C7
	Trapezius	Accessory (N. XI)	Also C2 - C4?
	Lattissimus dorsi	Thoracodorsal	C6 - C8
	Rhomboideus major	Dorsal scapular	C5
	Rhomboideus minor	" "	"
	Levator scapulae	Nn to levator scapulae	C3, C4
Intrinsic of shoulder	Deltoid	Axillary	C5, C6
	Supraspinatus	Suprascapular	"
	Infraspinatus	"	"
	Teres major	Lower subscapular	"
	Teres minor	Axillary	"
	Subscapularis	Both subscapulars	"
Flexor in arm	Biceps brachii	Musculocutaneous	C5, C6
	Coracobrachialis	"	C5 - C7
	Brachialis	"	C5, C6
Extensor in arm	Triceps brachii	Radial	C6 - C8
	Anconeus	"	C7, C8
Flexor in forearm	Pronator teres	Median	C6, C7
	Flexor carpi radialis	"	"
	Palmaris longus	"	C7, C8
	Flexor carpi ulnaris	Ulnar	C7?, C8, T1
	Flex. digitorum sup.	Median	C7 - T1
	Flex. digitorum prof.	Median and ulnar	"
	Flex. pollicis longus	Median	"
	Pronator quadratus	"	"
Extensor in forearm	Brachioradialis	Radial	C5, C6
	Supinator	"	"
	Ext. carpi rad. longus	"	C6, C7
	Ext. carpi rad. brevis	"	"
	Abd. pollicis. longus	"	"
	Ext.pollicis brevis	"	"
	Extensor digitorum	"	C6 - C8
	Ext. digiti minimi	"	"
	Ext. carpi ulnaris	"	"
	Ext. pollicis longus	"	C7, C8
	Extensor indicis	"	"

Table A.3 Innervation of muscles of the upper limb (continued)

MUSCLE GROUP	MUSCLE	PERIPHERAL NERVE	SEGMENTAL NERVE*
Thenar (thumb)	Abd. pollicis brevis	Median	C8, T1 (or C6, C7?)
	Flex. pollicis brevis	Median and ulnar	" "
	Opponens pollicis	Median	" "
	Adductor pollicis	Ulnar	C8, T1
Hypothenar (little finger)	Palmaris brevis	Ulnar	C7?, C8, T1
	Abd. digiti minimi	"	"
	Flex. dig. min. brevis	"	"
	Opponens digiti minimi		"
Other palm muscles	Lumbricals 1 & 2	Median	C8, T1 (or C6, C7?)
	Lumbricals 3 & 4	Ulnar	C7?, C8, T1
	Dorsal interossei (4)	"	"
	Palmar interossei (3)	"	"

* Question marks in association with the listings of segmental innervations indicate major points of disagreement.

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Appendix B. Taxonomies of Prehension

B.1 Prehensile Classifications for Adults

Prehensile classifications have been developed to study the characteristics of the human hand that give it such versatility. Some of these taxonomies are more anatomical, but most focus on functionality, particularly for evaluating remaining capabilities after accidents, disease or surgery. In Table B.1, these classifications are listed in chronological order. Each taxonomy offers new insights into the complexity of human prehension. Yet, across this diverse set, themes are repeated. For example, Schlesinger (1919) developed a minimum set of postures that focused on the hand as a tool and on object shapes and sizes. His open fisted cylindrical grasp is for large objects with long symmetry, the close fisted cylindrical grasp is for smaller objects with long symmetry, while the spherical grasp is for objects with radial symmetry. This latter one is also likely to be used for irregularly shaped objects. Griffiths (1943) used different terms for these same postures, as did many others. In order to identify similarities and to find unique functions, we have labeled the postures in the table with a bold-faced letter. Then, in Figure B.1, the unique postures are grouped in terms of what opposition or oppositions are occurring.

As described in Chapter 2, basic features of the hand emerge after studying these classifications. Slocum and Pratt (1946) identified three basic capabilities of the hand: the grasp (using the fingers against the palm), the pinch (thumb and finger pads), and the hook (flexing the fingers). The three postures described above fall into the 'grasp' category. In terms of the 'pinch' category, Schlesinger identified six different types (e.g., palmar pincer between the pads, tip prehension, etc). While numerous researchers have tried to further refine and expand these notions, Napier (1956) suggested that this grasp versus pinch dichotomy could be stated as an issue between power and precision grasping. Power and precision components of the hand can be used to match the power and precision requirements of tasks. One key difference between power and precision was pointed out by Landsmeer (1962): that precision grasping is for manipulating objects, while power grasping is for

Table B.1 Prehensile classifications chronologically. Bold faced letters following the posture name indicate which postures are similar (continued...)

Researchers	Posture names	
Schlesinger (1919)	open fisted cylindrical grasp **A** close fisted cylindrical grasp **B** spherical prehension **C** palmar prehension (pincer) **D** tip prehension **E** lateral prehension **F**	hook prehension **G** cyl. w/ add. thumb **B&F** flat/thin (2 fing.) pincer **I** large (5 finger) pincer **J** three-jaw chuck **K** nippers prehension **L**
McBride (1942)	whole hand grasping **J** palm, digits grasping **B**	thumb, finger grasping **D**
Griffiths (1943)	cylinder grip **B**	ball grip **C**
Slocum & Pratt (1946)	grasp **A, B, C** pinch **D**	hook **G**
Taylor (1948)	palmar prehens. (3 jaw chuck) **K** tip prehension **E**	lateral prehension **F**
Napier (1956)	power grip **T&F, B, A, A&F** precision grip **D, K, J**	combined grip **B&D** hook grip **G**
Landsmeer (1962)	power grasp **T&F, B, A, A&F**	precision handling **D,E, I, J, K, L**
Skerik et al. (1971)	power grip **T&F, B, A, A&F** two point palmar pinch **D** three point palmar pinch **K**	tip pinch **E** link grip (lateral pinch) **F** hook grip **G**
Jacobson & Sperling (1976)	coding system for fingers, finger positions, joint positions, contact surfaces, and orientation of object's longitudinal axis with respect to hand	
Cooney & Chao (1977)	grasp **B** palmar pinch **D**	tip pinch **E** lateral pinch **F**
Lister (1977)	span **A** power grasp **B** precision pinch **E** pulp pinch **D**	chuck grip **K** key pinch **F** hook grip **G** flat hand **M**
Sollerman (1980)	diagonal volar grip **T** transverse volar grip **B** spherical volar grip **C** pulp pinch **D**	tripod pinch **K, D&F&R** five-fingered pinch **J** lateral pinch **F** extension grip **O**
Kamakura et al. (1980)	power grip-standard **T** power grip-index ext. **R&F&T** power grip-distal **S** power grip-extension **T&F** parallel mild flexion grip **D** tip prehension **E** surrounding mild flexion grip **J'**	parallel extension grip **O** tripod grip **K** tripod grip-var. 1 **D&F** tripod grip-var. 2 **D&F;F&R** lateral grip **F** power grip-hook **G** adduction grip **Q**

Table B.1 (Continued) Prehensile classifications chronologically.

Researchers	Posture names	
Patkin	power grip **B**	pinch grip **D**
(1981)	external precision grip **D&F&R**	double grip
	internal precision grip **R&F&T**	(ulnar storage **T&D**)
Kapandji	cylindrical palmar **T, B**	tetradigital -pulp & side**D'**
(1982)	spherical palmar **C**	tetradig pulp to side**D&F**
	digito-palmar **B&F**	tetradigital by pulp **D**
	subterminal pollici-digital **D,I**	pentadigit-pulp & side **J'**
	terminal pollici-digital **E**	panoramic pentadigital **J**
	subtermino-lat. pollici-digital **F**	pentadigital cleft **A**
	interdigital latero-lateral **Q**	directional grip **R&F&T**
	tridigital grips **K, D&F&R**	gravity-dependent grips **G, M**
		dynamic grips **D,E,F,K,L,D&F&R**
Elliott and Connolly (1984)	palmar grip **B**	rock **D' <-> E**
	dynamic tripod **D&F&R**	radial roll **F**
	pinch **D <-> E**	index roll **D**
	squeeze **D**	full roll **D**
	twiddle **D <-> F**	interdigital step **Q <-> D**
	rotary step**D <-> F**	palmar slide **B&F**
	linear step **D**	
Lyons	encompass grasp **O**	lateral grasp **F**
(1985)	precision grasp **D**	
Iberall et al.	palm opposition	side opposition
(1986)	pad opposition	
Liu and Bekey	power grasp **B**	pulp pinch **D**
(1986)	cylindrical grip	chuck grip **K**
	span **A**	lateral pinch **F**
	precision pinch **E**	hook grip **G**
Kroemer	disk grip **J'**	lateral grip **F**
(1986)	collect enclosure **C**	precision or writing grip **D&F&R**
	power grasp **B**	hook grip **G**
	pinch or plier grip **D**	finger touch **R**
	tip grip **E**	palm touch **M**
Cutkosky	large diameter heavy wrap **A**	4 fing. precision grasp **D**
(1989)	small diameter heavy wrap **B**	3 fing. precision grasp **D**
	medium wrap **T**	2 fing. precision grasp **D**
	adducted thumb wrap **B&F**	disk precision grasp **J**
	light tool wrap **T**	spher. precision grasp **J'**
	disk power grasp **S**	tripod precision grasp **K**
	spherical power grasp **C**	lateral pinch **F**
	5 finger precision grasp **D**	hook,platform,push **G, M**

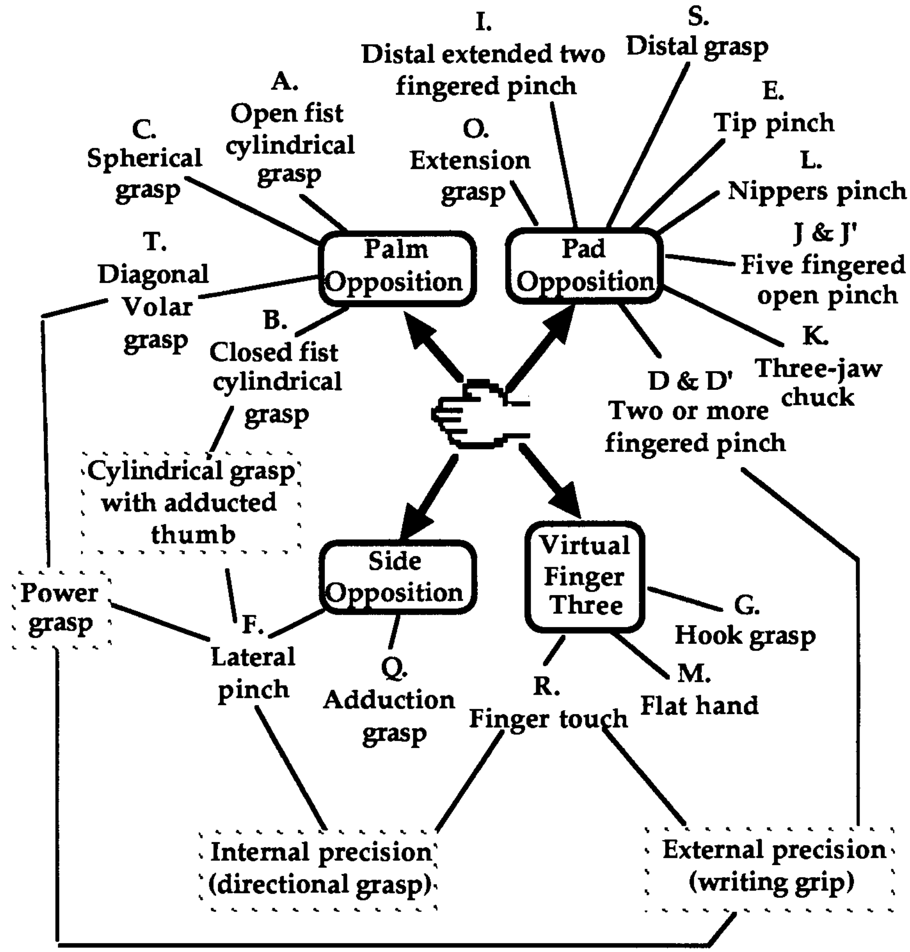

Figure B.1. Summary of postures identified by various researchers. Postures are grouped by oppositions. For palm opposition, there are four basic ways to hold the object against the palm with the fingers. For pad opposition, there are eight basic ways to use the fingers and thumb to hold and manipulate an object. For side oppositions, there are two basic ways to hold an object laterally. Note that some postures (e.g., power grasp, internal precision, etc.) are combinations of basic postures. These combined grasps are not labelled with a letter.

statically affixing the object in the hand. A bridge, or link, between these two poles is the lateral pinch (letter **F** in Table B.1 and Figure

B.1). Due to the anatomy of the hand and arm, this posture allows some manipulation while supplying more strength than two fingered palmar pinching. Finally, the glabrous skin of our hands, particularly at the pads, has a rich sensory capability, as outlined in Chapter 6. Whenever we put a finger against an object, the finger can act as an antenna to gather sensory information through cutaneous and proprioceptive mechanoceptors, while applying forces against the object.

Opposition space provides a framework for organizing and summarizing these classifications. Oppositions occur between two virtual fingers (VFs). Palm opposition occurs between the palm (VF1) and fingers (VF2) generally perpendicular to the palm, basically describing the way the entire hand 'grasps'. Pad opposition occurs generally parallel to the palm as the thumb pad (VF1) and finger pads (VF2) contact in order to pinch or impart motion to an object. Side opposition occurs generally transverse to the palm, bringing the thumb pad (VF1) to oppose the radial side of a finger (VF2), or adducting the fingers together. A virtual finger can also oppose a task-related force or torque. For example, a hook grasp (**G**) uses the fingers to counteract gravity when holding a suitcase. A finger placed on a fork or knife to press it harder is another example.

In the next four sections, the postures from Table B.1 are described using the opposition space framework as a guide. In the final section, a method of extending the table is suggested.

B.1.1 Palm oppositions

Palm oppositions have been identified based on four characteristics:

1) object shape,
2) object orientation,
3) size of hand opening (or object size), and
4) thumb placement.

In the open fist (**A**) and closed fist (**B**) cylindrical grasps, the thumb is wrapped around the object or around the back of the fingers. The object is generally cylindrically shaped, and it is held transverse to the palm. The spherical grasp (**C**) has been noted in two situations. The first is for regularly shaped objects with radial symmetry, such as spheres. However, Schlesinger noted that one of the important features of the human hand was its adaptable grip for irregularly shaped objects, where the palm could arch around the object.

Another palm opposition is seen when objects are held diagonally in the closed fist, identified by Sollerman (1980) as the diagonal volar grip and by Cutkosky (1989) as a medium wrap (**T**). The thumb sits resting on the radial aspect of the index finger, acting as a buttress holding the object. The object lies diagonally in the hand. This is reminiscent of Napier's power grasp (recall Figure 2.2a). However, in the power grasp, the thumb pad is usually placed against the object, the same location seen in the lateral pinch (**F**). For this reason, it is classified in Figure B.1 as a combination grasp consisting of the diagonal volar grasp (**T**) with lateral pinch (**F**). Another combination grasp is seen in holding beer mugs, where the the closed fist cylindrical grasp (**B**) combines with the lateral pinch (**F**) to create the posture that Schlesinger called the 'cylindrical grasp with adducted thumb.'

B.1.2 Pad oppositions

When contact is made between the thumb pad and one or more finger pads, pad opposition is observed. Pad oppositions are based on five characteristics:

1) the number of fingers used,
2) object shape,
3) size of hand opening (or object size),
4) the finger surfaces making contact, and
5) the flexion/extension state of the fingers.

The opposition between the thumb and one or more finger pads is posture (**D**). For simplicity, we are lumping the use of multiple fingers into one category, although some researchers have chosen to make this explicit (e.g., Cutkosky, 1989; Kapandji, 1982). Some researchers have noted the difference in the posture for prismatic objects (**D**) and for symmetrical objects (**D'**). If the researcher did not make the object shape distinctions, we have classified the pinch as (**D**). However, due to the anatomy of the hand, particular combinations of the fingers are effective in manipulating objects. For example, when the thumb, middle, and index fingers are used to hold a rounded object, the three jaw chuck (**K**) is created (e.g., Cutkosky, 1989; Lister, 1977; Schlesinger, 1919; Skerik et al,. 1971). When the hand is open wide for a large object and all five fingers are used, the five fingered open pinch is obseved (**J**) (e.g., Cutkosky, 1989; Kamakura et al., 1980; Schlesinger, 1919). This has been observed for objects with long symmetry (**J**) as well as radial symmetry (**J'**).

The contacting surfaces are important in distinguishing postures. When contact is made on the thumb and fingertips, a tip pinch (**E**) is observed when slight flexion of the fingers occurs (e.g., Kamakura et al. 1980; Schlesinger, 1919; Skerik, et al. 1971); for more pronounced extension, the nippers pinch (**L**) is observed (Schlesinger, 1919). When contact is made on the fingers below the pads but not using the palm, the distal grasp (**S**) is observed (e.g., Cutkosky, 1989; Kamakura et al., 1980). The extension grasp (**O**) is observed when all joints of the fingers are extended (e.g., Kamakura et al., 1980; Lyons, 1985). When just the distal interphalangeal joints are extended, the distal extended two fingered pinch (**I**) has been observed (Schlesinger, 1919).

Interestingly, the external precision, or writing grip, (Elliott and Connolly, 1984; Kamakura et al., 1980; Patkin, 1981) is not a simple pad opposition. Recalling Figure 2.4b, the thumb opposes the index finger pad in a two fingered pinch (**D**). At the same time, the radial side of the middle finger is also opposing the thumb: this is a lateral pinch (**F**). The cleft of the thumb makes contact with the object, in order to steady it; this is a finger touch (**R**), which in effect is a virtual finger three.

Some postures are used to hold multiple objects, such as chopsticks (two independent objects) or scissors (two constrained objects). For these postures, multiple oppositions are occuring (Kamakura et al., 1980; Kapandji, 1982). For example, one chopstick is held in the thumb, index, middle finger using a pinch (**D**) and a lateral pinch (**F**). The other chopstick is held in a lateral pinch (**F**) between the thumb and ulnar fingers, with the help of the cleft of the thumb (**R**).

B.1.3 Side oppositions

Side opposition occurs generally transverse to the palm. There are two types of side opposition. The lateral pinch (**F**) occurs between the thumb and radial side of the digits (Kroemer, 1986; Lyons, 1985; Liu & Bekey, 1986), and is seen in holding a key to turn a lock. More likely, it is seen in combination with palm opposition, as in Napier's power grasp. The other side opposition is the adduction grip (**Q**), between the radial and ulnar sides of the fingers (Kamakura et al., 1980; Kapandji, 1982), as one might hold a chocolate cigarette, as seen in Figure 2.4a.

B.1.4 Virtual finger three

A virtual finger three (VF3) is used in postures whenever a hand surface is used to counteract a task related force or torque. This has been observed in the hook grasp (**G**), and also in the flat hand (**M**) as in holding a small tray (Kapandji, 1982; Lister, 1977). Kapandji (1982) notes another way the hand can be used in a gravity-dependent grip. This is when it is used as a spoon or shell. Another example of a VF3 is when one finger touches an object, acting as an antenna to direct the object or gather sensory information. Interestingly, the directional grasp (or internal precision grasp) is a combination of a finger touch (**R**) and lateral pinch (**F**). As seen in Figure 2.4c, it can also be a combination of a finger touch (**R**), lateral pinch (**F**), and a diagonal volar grasp (**T**).

Table B.2 Some taxonomies of development of prehensile skills in infants. This chronological list is limited.

Researchers	Posture names	
Halverson (1931)	contact primitive squeeze squeeze grasp hand grasp palm grasp	superior-palm grasp inferior-forefinger grasp forefinger grasp superior forefinger grasp
Twitchell (1965)	traction full grasp reflex	fractionation of grasp reflex instinctive grasp reaction
Touwen (1971)	voluntary palmar grasp radial palmar grasp scissor grasp	scissor-pincer grasp pincer grasp
Hohlstein (1982)	in addition to Halverson's grasps: 3 surface contact fingers to ulnar palm fingers to middle palm fingers to radial palm sides of fingers grasp	thumbpad to fingers thumbpad to combination 3-4-5 pads thumbpad to 2 or 3 side thumbpad to 2-3-4-5 pads thumbpad to 2-3 pads thumbpad to index pad

B.2 Prehensile Classifications for Infants

Descriptions of emergent prehesile behavior have been developed for infants. For example, Halverson (1931) developed a taxonomy of grasps after studying infants from 16 to 52 weeks of age. According to Halverson, infants start making contact and primitive squeezes at around 20 weeks old. The first time they exhibit an actual grasp, the squeeze grasp, is at around 24 weeks old. It is in the palm grasp, at 28 weeks old, where infants first actively use their thumb in opposition to the fingers.

Table B.2 has a limited summary of some of the research into developmental prehension. Interested readers are encouraged to read the literature cited in the table, as well as recent work by Forssberg, Kinoshita, Eliasson, Johansson, Westling, & Gordon (1992) and von Hofsten & Ronnqvist (1988).

B.3 Postures as Combinations of Oppositions

Figure B.1 has summarized the postures developed in prehensile classifications for the last century. It shows that prehensile postures can be viewed as either pad, palm, or side opposition. In addition, it shows that some postures are combinations of these oppositions, and that a VF3 can be used to counteract task forces or torques or sense the state of the object.

In Chapter 2, we discussed how palm, pad, and side oppositions can be used in combinations to hold one or more objects. Using this opposition space approach, prehensile postures can be described, as shown in Table B.3. Shown are the opposition types and virtual finger mappings for one, two, and three oppositions in grasps. There are eight possible combinations of pad, palm, and/or side oppositions (e.g., palm alone, pad alone, palm and pad, etc). For each combination, there are differing possible virtual finger mappings. For palm opposition, the palm is used as VF1. For pad opposition, the thumb is used as VF1. For side opposition, the thumb is usually used, however, in the adduction grasp, the index finger is used. For VF2, one or more fingers can be used. Fingers not being used in VF1 and VF2 can be used in VF3, as seen in the last column of the table. Fingers can be used alone as gravity dependent grasps or finger touches.

Table B.3 can be examined for the symbolic postures listed in Table B.1. For example, grasp 2 in Table B.3, consisting of one

Table B.3 Postures consisting of combinations of oppositions. For each virtual finger, one or more real fingers or the palm are used. When fingers are not being used in one of these oppositions, they may be used as aVF3 alone or in tandem with the oppositions. P=palm, T=thumb, I=index finger, M=middle finger, R=ring finger, L=little finger (adapted from Iberall et al., 1988 and Iberall et al., 1991) (continued)

	ID	Opposition 1 OPP	VF1	VF2	VF3 (optional)
One opposition postures					
I	1.	PALM	P	I-M-R-L	T
	2.	PALM	P	T-I-M-R-L	
	3.	PALM	P	I-M-R	T, L
	4.	PALM	P	T-I-M-R	L
	5.	PALM	P	M-R-L	T, I
	6.	PALM	P	T-M-R-L	I
	7.	PALM	P	I-M	T, R-L
	8.	PALM	P	T-I-M	R-L
	9.	PALM	P	M-R	T, I, L
	10.	PALM	P	R-L	T, I-M
	11.	PALM	P	I	T, M-R-L
	12.	PALM	P	T-I	M-R-L
	13.	PALM	P	M	T, I, R-L
	14.	PALM	P	R	T, I-M, L
	15.	PALM	P	L	T,I-M-R
	16.	PALM	P	T	I-M-R-L
II	17.	PAD	T	I-M-R-L	
	18.	PAD	T	I-M-R	L
	19.	PAD	T	M-R-L	I
	20.	PAD	T	I-M	R-L, radial P
	21.	PAD	T	M-R	I, L
	22.	PAD	T	R-L	I-M
	23.	PAD	T	I	M-R-L
	24.	PAD	T	M	I, R-L
	25.	PAD	T	R	I-M, L
	26.	PAD	T	L	I-M-R
III	27.	SIDE	T	I	M-R-L
	28.	SIDE	T	I-M	R-L
	29.	SIDE	T	I-M-R	L
	30.	SIDE	T	I-M-R-L	
	31.	SIDE	T	M-R-L	I
	32.	SIDE	T	R-L	I-M
	33.	SIDE	I	M	T,R-L
	34.	SIDE	M	R	T, I,L

Table B.3 (continued) Postures consisting of combinations of oppositions. For each virtual finger, one or more real fingers or the palm are used. When fingers are not being used in one of these oppositions, they may be used as aVF3 alone or in tandem with the oppositions. P=palm, T=thumb, I=index finger, M=middle finger, R=ring finger, L=little finger (adapted from Iberall et al., 1988 and Iberall et al., 1991)

	ID	Opposition 1			Opposition 2			VF3
		OPP	VF1	VF2	OPP	VF1	VF2	(optional)
Two opposition postures								
IV	35.	PALM	P	I-M-R-L	SIDE	T	I	
	36.	PALM	P	I-M-R	SIDE	T	I	L
	37.	PALM	P	M-R-L	SIDE	T	I	
	38.	PALM	P	I-M	SIDE	T	I	R-L
	39.	PALM	P	M-R	SIDE	T	I	L
	40.	PALM	P	R-L	SIDE	T	I-M	
	41.	PALM	P	I	SIDE	T	I	M-R-L
	42.	PALM	P	M	SIDE	T	I	R-L
	43.	PALM	P	R	SIDE	T	I-M	L
	44.	PALM	P	L	SIDE	T	I-M-R	
	45	PALM	P	R-L	SIDE	T	M	I
V	46.	PALM	P	M-R-L	PAD	T	I	
	47.	PALM	P	R-L	PAD	T	I-M	
	48.	PALM	P	L	PAD	T	M-R	I
	49.	PALM	P	M-R	PAD	T	I	L
	50.	PALM	P	R-L	PAD	T	M	I
VI	51.	PAD	T	I	SIDE	T	M	R-L, radial P
	52.	PAD	T	R-L	SIDE	I	M	
	53.	PAD	T	I-M	SIDE	T	P-R-L	
Three opposition postures								**Opposition 3**
								OPP VF1 VF2
VII	54.	PALM	P	R-L	PAD	T	I	SIDE T M
Virtual finger 3 only								**VF3**
VIII	55.							P-T-I-M-R-L
	56.							I-M-R-L
	57.							I-M-R
	58.							I-M
	59.							I

opposition, is Napier's coal hammer grasp, while grasp 35 is the power grasp, consisting of two oppositions. Grasp 20 is the three-jaw chuck, while grasp 51 is the external precision grasp. Grasp 43, with the index finger as VF3 sticking out as an antenna, is the internal precision grasp. Grasp 33 is the adduction grip. Grasp 56 is the hook grasp, while grasp 55 is used when a waiter holds a big tray.

Only contiguous mappings have been listed in these tables; other noncontiguous mappings could possibly occur, useful in some highly constrained situation.

Appendix C. Computational Neural Modelling

This appendix gives some simple background material for understanding the computational models presented in this book. An excellent reference for more background is Rumelhart et al. (1986b) and McClelland et al. (1986). Other review papers include Arbib (1987) and Lippmann (1987). In addition, there are commercially available software products that allow models to be implemented and developed on personal computers and distributed workstations.

C.1 Introduction

The power of a computational model using a neural network architecture is in generalizing from a few sample points. Using supervised learning, it would be similar to a child learning to grasp: the first time, some posture is chosen, and the object drops from her hand. Failure in the task tells the brain that parameters were chosen incorrectly, and adjustments are made so that success is more likely the next time. Modification can be made to either the parameter values or to the selection of the parameters; e.g., using more fingers to provide more force, realizing that the texture of the object surface is important in choosing a grasp. Repeated trials allow the resetting of parameters, until a successful grasp is selected. Generalizations are made. This allows the child to eventually start picking up objects that she has never interacted with before.

A model, according to Webster's dictionary, is a representation that shows the construction or serves as a copy of something. Churchland and Sejnowski (1988) compare the usefulness of models being developed in the emerging field of cognitive neuroscience. Realistic models can be used as predictive tools for some aspect of nervous sytem dynamics or anatomy, whereas other models are simplifying ones and can demonstrate how the nervous system could be governed by specific principles. A conceptual neural model can be at different levels: it can model the internal behavior of neurons, the interactions of neurons in neural networks, or even the passing of information from one neural assemblage to another. Conceptual models are important for understanding complex systems; however, when simplifying assumptions are made in a conceptual model, they allow one to focus at the desired level of complexity so that key relationships are highlighted. These models act to suggest computational models which explicitly specify details of the system by showing solutions to mathematical systems. Computational modelling allows one to simulate a conceptual model in order to test its validity. However, the designer of the computational version has to make decisions about various aspects of the conceptual model in order to actually implement it on a computer. Some examples:

1. **Neuronal Models.** Conceptual models exist for understanding the behavior of individual neurons. Dendrites, acting as inputs, sum up activity coming into a neuron, and if threshold is reached, an action potential travels down the axon to cause neurotransmitters to be released. In order to model this on a computer, parameters must be set using differential equations that describe membrane potentials, thresholds, cable propagation, etc.
2. **Control Theoretic Models.** Neuronal activity is fit into control equations that describe feedback and feedforward control using data transformations (e.g., integration and differentiation). For example, neurophysiologists have shown the existence of burst neurons, and Robinson (1981) constructed a control theoretic models around such neurons, showing how a computation can be performed. In another example, Allen and Tsukahara (1974) developed a conceptual model showing the relationship between various cerebral and cerebellar areas. From this, Kawato and colleagues constructed a computational model using standard feedforward-feedback control theory (Kawato et al., 1987b) and using neurons to simulate motor cortex (Kawato et al., 1987a).
3. **Network Models.** Consisting of billions of neurons making synapses with one another, the CNS can be modelled using massively parallel network of neurons. For example, when looking at one's arm, retinal inputs and eye muscle activity will create a pattern of incoming activity into the CNS. Kuperstein (1988) constructed a massive network that correlates retinal and eye muscle activity to an arm configuration. Network design decisions include: in what coordinate frame is the information, how is it transformed, what size networks are needed, how can learning occur. The mathematics of nonlinear dynamical systems in high-dimensional spaces are used to construct these models.

4. **Assemblage Models.** To capture the essence of behavioral data, a conceptual coordinated control program model (Arbib, 1981) can be written to describe the activation of schemas (units of motor control and interactions with the environment). A schema can be modelled as many networks (a network assemblage) passing control information (activation lines) and data (e.g., target location). This conceptual model can be implemented in a language such as **RS** (Lyons & Arbib, 1989).

Computational network models that involve parallel distributed processing (Rumelhart et al., 1986b) have been called connectionist models (Feldman & Ballard, 1982) or artificial neural networks. The key ingredient to this type of information processing is that it involves the interactions of a large number of simple processing elements that can either inhibit or excite each other. Thus they honor very general neurobiological constraints, but using simplifying assumptions, are motivated by cognitive phenomena and are governed primarly by computational constraints (Churchland & Sejnowski, 1988). Each element can be a simple model of a neuron, as in the third example above, or it in itself can be a network of neurons, as in the network assemblage example. Control theoretic models, while not usually involving the interaction of a large number of elements, are useful for bringing to bear the tools of modern control theory for information processing, as was seen in Chapter 5. Models of individual neurons are not discussed in this book, since we are more interested in how networks of neurons can perform computations.

Parallel distributed processing is neurally-inspired, due to two major factors (Rumelhart et al., 1986a). The first factor is time: neurons are slow and yet can solve problems dealing with a large number of simultaneous constraints in a relatively short time-period. Feldman (1985) called this the '100 step program constraint', since one second of processing by neurons that work at the millisecond range would take about 100 time-steps. The second reason is that the knowledge being represented is in the connections, and not in 'storage cells' as in conventional computers. If it is an adaptive model, a distributed representation will allow the network to learn key relationships between the inputs and outputs. Memory is constructed as patterns of activity, and knowledge is not stored but created or recreated each time an input is received. Importantly, as more knowledge is added, weights are changed very slightly; otherwise, existing knowledge will be wiped out. This leads to various constraints on processing capabilities, as described in the next section.

C.2 Artificial Neural Networks

Artificial neural networks consist of processing units. Each unit has an activation state and are connected together through synapses[1] in some pattern of connectivity. Rules govern how information is propated and how learning occurs in the network. The processing units can represent individual neurons or else concepts (that can either be individual cells themselves or groups of cells). The issue, more importantly, for these models is how a computation is performed without regard so much as to at level it is working. In the next subsections, we describe some of the decisions that a network designer must make, and what are the reasons and advantages for doing so.

C.2.1 Activation functions and network topologies

Different models are used within neural network models for the processing units. The most common is the McCulloch-Pitts type neuron, where each unit simultaneously takes a weighted sum of its inputs (dendrites) at each network time step Δt, and if threshold is reached, the cell body discharges at a certain firing frequency. The output of such a neuron is seen in the left side of Figure C.1. If we consider the weighted sum of a neuron's incoming signals to be its input, I, and its state to be u, then a McCulloch-Pitts neuron operates according to the assignment u = I. The result is then thresholded to produce its output. An alternative to this discrete model is the leaky integrator model, where the neuron's behavior is described by a first-order linear differential equation:

$$\tau*(du/dt) = -u + I \tag{1}$$

where τ is the unit's time constant. In simulating such a neuron, τ must be greater than the simulation time step Δt. As the time constant approaches the simulation time step, this rule approaches the McCulloch-Pitts rule. The output of such a neuron is seen in the right side of Figure C.1. If τ = dt, we see that du = -u + I. So, in the simulation,

[1] A synapse is a small separation between the axon (output fiber) of one neuron and the cell body or fibers of another neuron. A neuron can synapse onto itself as well.

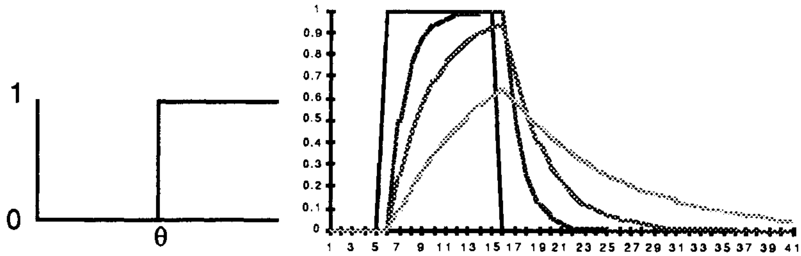

Figure C.1 McCulloch-Pitts neuron vs Leaky Integrator. Activation is on the X axis and output is on the Y axis. For the leaky integrator, several values of t are shown. See text for details

$$u(t+1) = u(t) + du = u(t) + (-u(t) + I) = I \qquad (2)$$

which is precisely the McCulloch-Pitts unit. The advantage of using the leaky integrator model is that it provides a continuous time model of the neural network.

Each neuron has a state, or activation level. An activation function is a deterministic function that computes a neuron's state as a function of the neuron's input. The strength of the connection from one neuron to another can be attenuated or enhanced through the use of a weight, which represents the synaptic strength. Weights on the inputs adjust the influence of the input. The activation function for a McCulloch-Pitts neuron is:

$$a_i = \sum_j w_{ij} o_j \qquad (3)$$

where the activity of each input into neuron i is multiplied by an associated weight w_{ij} (the strength of connection between neuron i and neuron j) and these products are summed to produce the activation of that neuron. Positive weights represent excitatory connections; negative weights inhibitory ones. The state of activation is actually time-varying (i.e., $a_i(t)$), so that the state of the system can be represented at any time t. An activation of zero usually means that the neuron is inactive. Activation functions can be discrete (mapping the inputs to a binary value or a small and limited set of values) or

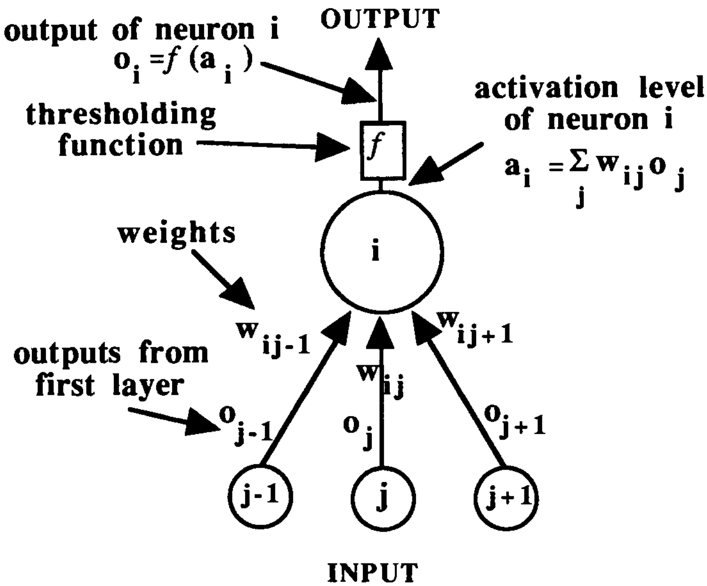

Figure C.2 Simple pattern of connectivity between one input layer and one output layer.

continuous (taking on real values that can be bounded between two values or unbounded). A popular model, called a linear threshold unit, uses an activation function that maps onto the binary set {0,1}. As seen in Figure C.1, a McCulloch-Pitts neuron is a linear threshold unit. A quasi-linear (or semi-linear) activation function[2] is a non-decreasing and differentiable function that produces values within an interval.

To model a neuron's activation after a certain threshold is reached, an output function f is used, producing the output (on the axon) from neuron i as follows:

$$o_i = f(a_i) \tag{4}$$

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[2]This is also called a squashing function.

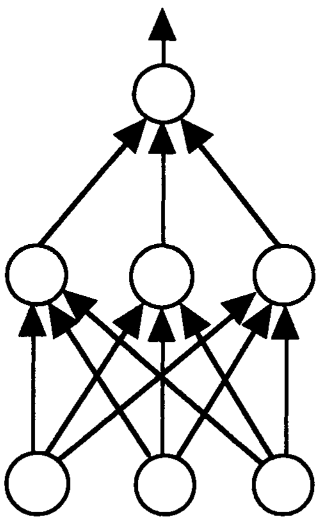

Figure C.3 Simple pattern of connectivity in multi-layered network, containing one input layer, one hidden layer, and one output layer.

The function *f* can be the identity function, or more usually, it is a threshold function that ensures that a neuron only outputs a signal when its activation exceeds a certain value, as typically seen in real neurons.

In parallel distributed processing models, neurons are connected in some pattern of connectivity, or network topology. A feedforward network is a set of neurons connected in such a way that there are no cyclic paths. This type of network has no dynamics; that is, after an input pattern is applied to the network, within a finite number of 'steps' (synaptic delays) equal to the length of the longest path from input to output, the network will settle into a static state of neural activation. Such a network is seen in Figure C.3. This feedforward network has three layers. Certain neurons are defined to be 'input units' and certain ones are 'output units'. Intermediate units, which are not input or output are called 'hidden units'. In 1969, Marvin Minsky and Seymour Papert demonstrated that adding a layer of neurons hidden between the input layer and output layer can allow the inputs to be recoded into a sufficiently similar structure for correct processing. This in effect creates a higher dimensional input space, allowing more 'elbow room' for the computation. It is often the case that these hidden units attend to features of the input patterns important to the network's computation, so experimenters analyze their responses to determine how the network operates.

A representation can either be encoded or decoded. With a decoded input representation, there is a separate unit for each possible input pattern. Since only one of these is active at a time, the network must see every possible input pattern during training. The disadvantage is that there is a combinatorially explosive number of units. However, the weight modification rule is then simple, since input units can drive output units with excitatory synapses, and inhibit others. Other advantages of using highly decoded representations include fault tolerance, sufficiency of components with relatively poor dynamic range, and ease of local feature extraction. The ease of learning a function will depend on the degree to which the output representation is related to the input representation on which it depends. With an encoded input representation, the activation of output units depends on complex nonlinear interactions between the inputs, and therefore multiple layers for computing more complex functions are needed.

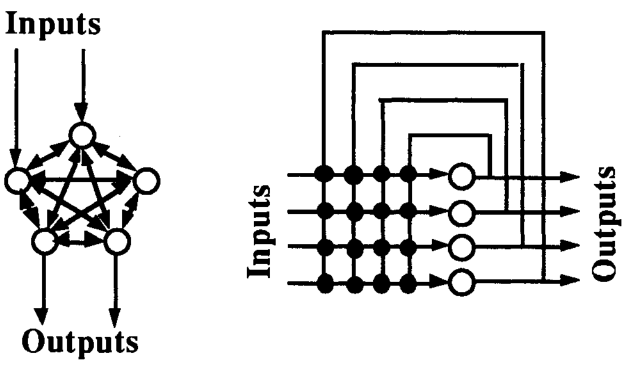

Figure C.4 Recurrent networks that are completely connected. Both networks receive input directly from every other unit.

The alternative to feedforward networks is the <u>recurrent</u> or <u>feedback</u> network, as seen in Figure C.4. These examples are both completely connected recurrent networks; i.e., every unit receives input directly from every other unit, hence the number of connections is equal to the square of the number of units. As before, some units are defined as input units, while others are defined as output units. Recurrent networks are capable of more complex behavior, in particular rather than converging on a single state, they may settle into limit cycles of neural activity. Such networks are in general harder to analyze, but are necessary when dynamic behavior is desired.

C.2.2 Adaptation in neural networks

Computational models can be adaptable or non-adaptable. Non-adaptive networks have fixed synaptic weights and behavior, whereas adaptive networks modify their synaptic weights (and therefore their behavior) over time according to the stimuli they experience. Hybrid nets also exist which have 'pre-wired' non-adaptive portions interacting with adaptive portions, as was seen in the Kuperstein (1988) model in Chapter 4[3]. A non-adaptive network might model a peripheral area which does not change its behavior over time, such as the spinal circuitry subserving the knee-jerk reflex. Adaptive neural nets would be used to model parts of the brain concerned with learning, which change their behavior with experience.

In an adaptive neural network, the synaptic connection weights modify themselves based on locally available information, that is the 'activity levels' in the pre- and post-synaptic neurons. This is one of the compelling properties of neural networks - that while the individual units are performing simple computations on the small scale, the overall network may develop complex emergent behavior. There are two classes of adaptation rules - supervised and unsupervised. Supervised adaptation rules contain some measure of the desired behavior of the network, while unsupervised adaptation rules do not. (Thus networks governed by supervised learning develop behavior defined by the training signal, whereas those governed by unsupervised learning respond to properties of the patterns presented, extracting repeated information or correlations in the data.)

In neural network models, this adaptation is captured in a <u>learning rule</u>. In 1949, D. O. Hebb described a rule which has been generalized to the following: adjust the strength of the connections

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[3]An adaptive network can also be used as if it were non-adaptive. For example, once the Model Network in the Jordan (1988) network learned the inverse kinematics of the arm, it was used as a fixed network while the Sequential Network learned the sequences.

between two units in proportion to the product of their simultaneous activation. More formally, the Hebbian learning rule can be stated as follows (see left side of Figure C.5):

$$\Delta w_{ij} = \eta\, o_i\, o_j \tag{5}$$

where the output of neuron j is multiplied by the output of neuron i and by a constant of proportionality η (the learning rate) to produce the amount by which to change the weight between them. Presynaptic signals and postsynaptic signals are used to modify the weights, without benefit of a teacher (i.e., this is unsupervised learning). The larger η is, the larger the changes in the weights. The advantage of this rule is that information is locally available for determining how to change the weights. A disadvantage of such a simple learning rule can be seen in a network that is trying to associate one pattern with another. Two patterns are presented and weights are modified so that, if only one pattern is presented the network can produce the second one correctly. Using Hebbian learning, this can happen only when all patterns are completely uncorrelated.

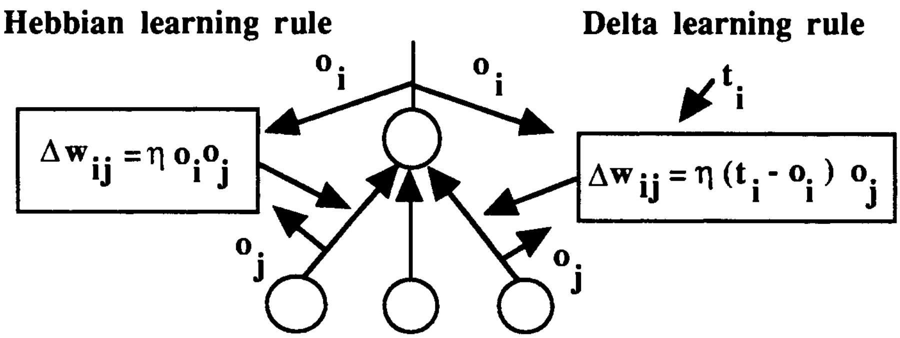

Figure C.5 Two different learning rules for updating the synaptic weights. On the left, Hebbian learning is shown, where weights are adjusted in proportion to the product of two neurons's simultaneous activation. On the right, the delta rule is shown, where a teacher is needed to compute the error between the desired output and actual output.

Another common rule which uses the presynaptic signal and postsynaptic error is called the delta rule[4] (or Widrow-Hoff rule), and it uses a target value as follows (right side of Figure C.5):

$$\Delta w_{ij} = \eta \, (t_i - o_i) \, o_j \tag{6}$$

Instead of using the output of neuron i to determine by how much to change the weights, the actual output o_i is first subtracted from the desired output t_i. To do this, supervised learning is used. A small training set is provided to the network for learning some part of the task space. The training set is a collection of input/output pairs (or patterns) that identifies to the network what the output should be for a given set of inputs. For linear units, this rule minimizes the squares of the differences between the actual and desired output values summed over the output neuons and all pairs of input/output vectors (Rumelhart, Hinton & Williams, 1986a).

The delta rule can be derived from a technique called gradient descent. 'Gradient descent' means 'go down hill' in a mathematical sense. For a traveller in a hilly area, define z to be the person's altitude, x to be longitude (i.e., how far east she is located) and y to be latitude (how far north she is). Then z is a function of x and y: the altitude of the ground varies with its x-y location. The variables x and y are independent ones and the traveler can shift these at will by walking. Since the traveler's altitude changes as x and y do, z is the dependent variable. The gradient, or change, of z is the vector of partial derivatives of z with respect to its independent variables: $(\partial z/\partial x, \partial z/\partial y)$. In this case the gradient represents a horizontal vector which points in the direction of travel for which z increases most rapidly. The gradient descent rule simply says "move in the direction opposite to which the gradient vector points". Mathematically, it is written as:

$$(\Delta x, \Delta y) = -\eta(\partial z/\partial x, \partial z/\partial y) \tag{7}$$

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[4]An early model was a perceptron, which consisted of linear threshold units using the delta rule for synaptic weight modification (Rosenblatt, 1962).

where η is a small positive number defining the traveler's speed. Gradient descent is a very general technique: first, define some quantity to minimize (a dependent variable) in terms of controllable quantities (the independent variables). Then, take the gradient and use it, as shown above, to 'tweak' the independent variables, moving 'downhill'. The process is repeated until a minimum value is reached, at which time the gradient will be zero.

In a neural network, the independent variables are the synaptic weights. The dependent value to be minimized is taken as some measure of the difference between the actual and desired performance of the network. Thus, gradient descent is used to decrease the performance error. For example, imagine a network with a single output neuron (neuron i), which is being trained with a pattern p which is a collection of input/output pairs. Let the desired output value be t_{pi}, and the actual value o_{pi}. Define the error to be $E = 1/2(t_{pi} - o_{pi})^2$. Then for all weights w_{ij} which feed into unit i,

$$\partial E/\partial w_{ij} = -1(t_{pi} - o_{pi})\partial o_{pi}/\partial w_{ij} \tag{8}$$

Recalling the neuron definition equations,

$$a_i = \Sigma w_{ij} o_j, \text{ and } o_i = f(a_i) \tag{9}$$

then, by the chain rule for differentiation,

$$\partial E/\partial w_{ij} = -1(t_{pi} - o_{pi})f'(a_i)o_j, \tag{10}$$

Now, by the gradient descent definition,

$$\Delta w_{ij} = -\mu\partial E/\partial w_{ij} = \eta(t_{pi} - o_{pi})f'(a_i)o_j \tag{11}$$

For a linear neuron $f'(a_i) = 1$ for all a_i, so

$$\Delta w_{ij} = \eta(t_{pi} - o_{pi})o_j \tag{12}$$

which is the delta rule. (The complete derivation is shown in Rumelhart et al., 1986a).

For networks with hidden layers, the <u>generalized delta rule</u> is used (see Figure C.6), which states:

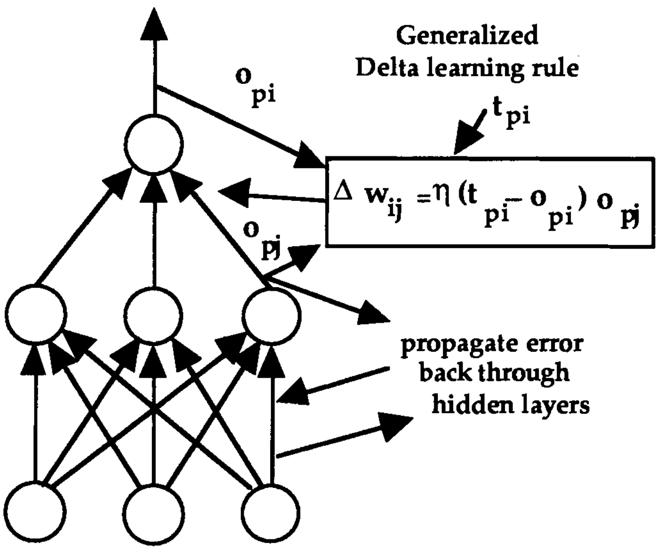

Figure C.6 The generalized delta rule is shown, where a teacher is needed to compute the error between the desired output and actual output.

$$\Delta w_{ij} = \eta \, (t_{pi} - o_{pi}) \, o_{pj} \tag{13}$$

where the actual output o_{pi} is subtracted from the desired output t_{pi} for a particular input/output pair, p. For the output layer of a layered network, it is the same as the delta rule. For the other layers, the error, E, is still dependent on the weights, but a continuation of the chain rule must be applied to show the mathematical dependence. The error is propagated backwards.

To perform a computation in an adaptive neural network using the generalized delta rule, two phases must occur. At the start, weights are initially random, or arbitrary, values. The training set is presented to the network, one input/output pair p at a time. The first phase is a forward computation using equation (3) to sum the products of the inputs and weights to each neuron in order to produce an activation value. Equation (4) is used to threshold the result. This computation propagates forward for all neurons in the network. The results at the output neurons are then compared to the desired outputs stored in the training set; if they are the same, the network has learned the correct computation for that input. If they are different, the second phase occurs. During the second phase, the weights between the neurons are adjusted by propagating the error backwards using equation (13) to change the weights.

Weight space refers to the space of all possible weight combinations. It is generally true that the more weights available to adjust (i.e., the higher the weight space dimensionality), the more likely it is that a solution will be found. As a simple example consider the simple mapping shown in the table in Figure C.7. Four patterns are mapped into a single value, computing an Exclusive-OR function. A binary representation is shown at the left. A 'distributed' representation is also shown that encodes the same information in a four element, rather than two element, vector. For each encoding, a network is shown in Figure C.7. For the binary representation, there are no connection weights such that a single neuron can achieve the mapping. However, with the distributed representation, it is a simple matter to find a set of weights which solve the problem. There are several arguments why this strategy tends to be successful, but it suffices to say that mappings are more likely to be realized in a higher dimensional space.

Input		Output
Binary	**Distributed**	
0 0	**0 0 0 1**	**0**
0 1	**0 0 1 0**	**1**
1 0	**0 1 0 0**	**1**
1 1	**1 0 0 0**	**0**

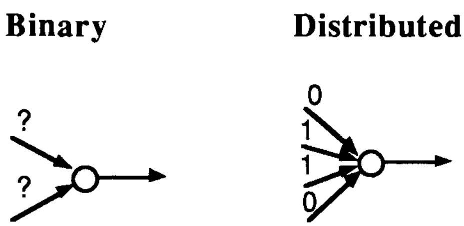

Figure C.7 Two encodings of the same function.

In order to use gradient descent, a continuous, nonlinear activation function f is needed, since the derivative is used and because hidden units are part of the network topology. The disadvantage of this technique is that a local minimum could be reached which is not a true minimum. There is also no indication of how long multiple repetitions of presenting the input/output pairs are needed in order to get the error reduced to some small value close to zero.

C.2.3 Processing capabilities in neural networks

Some of the types of information processing performed by artificial neural networks include pattern association, pattern completion, pattern classification, and regularity discovery. In pattern association, a pattern is not stored; instead, the strength of the connection between two neurons adjusts, so that the next time an input pattern is seen at neuron j that causes it to output o_j, the weight w_{ij} has been set to the correct value to produce the associated pattern o_i as output from neuron i. Pattern completion involves filling in a missing portion of a pattern. For example, a pattern is associated with itself, in what is called auto-association, so that when a degraded version of the pattern is presented to the network, it can reconstruct the complete pattern. Degraded patterns occur when incomplete information is available, such as in partially-hidden objects, or noise on a signal.

Particularly useful properties of artificial neural networks include default assignments, generalization, and graceful degradation. A computational architecture that can generalize about how to grasp objects never seen before is better than a system where every possible associated pattern must be accounted for. In these artificial neural networks, where similar input patterns lead to similar outputs, only a few sample training points are needed. Similar patterns reinforce the strengths of the weights between neurons. By presenting a pair with some noise added, the system will learn the central tendency. Default assignments as well come from this same property. Also, one does not need a perfect copy of the input to produce the output.

C.3 Network Example: Heteroassociative Memories

A single-layer, feedforward neural network may be used as a heteroassociative memory. That is, it can be trained to produce an arbitrary output pattern given a paired input pattern. We consider the case where the network has an n-vector output of linear summation units. Also, we assume n input lines, each of which connects to all the output units. The input and outputs both consist of real numbers, although much of what's said will apply to binary neurons as well. The topology is shown in Figure C.8. Note that there are n^2 connection weights, since each input connects to each output. Questions regarding this type of network include:

1) given the patterns to be stored, how are the connection weights set to produce the desired behavior?
2) what is the network's capacity (i.e., how many input/output pairs can it 'store')?
3) are there any restrictions on what the patterns can be?

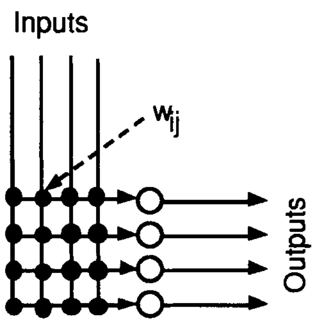

Figure C.8. Heteroassociative memory with four inputs and four outputs.

Since each unit is a linear summer, its output is the dot product of its input and the vector of connection weights impinging on it; i.e. for unit i, the incoming weights are w_{ij}, j= 1 to n, and the output is:

$$O_i = \Sigma w_{ij} I_j \tag{14}$$

where I is the input vector and O is the output vector. If w_i is a row vector of weights for neuron i, then

$$O_i = w_i I \tag{15}$$

If W is the matrix of weights for the whole memory (i.e., the i^{th} row is w_i), then the behavior of the memory can be written

$$O = WI \qquad (16)$$

Now, if there are p input/output pairs, we can define two n x p matrices, $\underline{I}$ and $\underline{O}$, where the columns of $\underline{I}$ are the p input patterns and the columns of $\underline{O}$ are the corresponding p output patterns. Then we have

$$\underline{O} = W\underline{I} \qquad (16)$$

for correct performance. But this equation also defines W and answers our first question. By inverting it we obtain:

$$W = \underline{O}\,\underline{I}^{-1} \qquad (17)$$

which gives an explicit formula for computing W (although it is necessary to perform the time consuming task of inverting $\underline{I}$.) It also provides an upper limit on p (the memory's capacity), answering the second question: $\underline{I}$ is only guaranteed to be invertible if $p \leq n$. For the remainder of the discussion we will assume $p=n$, that is the matrices are square. The input patterns must then be linearly independent, since $\underline{I}$ must be invertible (its determinant must be non-zero).

Computing W can be time consuming, as mentioned above, but a special case occurs when all the input patterns are orthonormal. In this case, $\underline{I}^{-1} = \underline{I}^T$, and the computation of W simply requires a single matrix multiplication. The orthonormal condition is often assumed true when the patterns are binary, long (large n), and sparse (mostly zero), because they tend to be orthogonal (their dot products are likely to be zero). If they all have about the same number of one's, then they can all be scaled down by that number to be roughly normal (of unit magnitude). The resulting performance of the memory is close to correct. For non-orthonormal situations, there is the option of applying a gradient descent technique (e.g. the delta rule) to iteratively learn the weight matrix.

C.4 Processing Example

As was shown in the previous section, a heteroassociative memory allows two patterns to be associated with one another, such that one pattern (the input pattern) triggers the other pattern to appear at the output units. For this example, a network with three inputs and three outputs (all linear) will be used, as seen in Figure C.9. Assume your only sense is vision and there are only three objects that you know about: mug, pen, and key. Suppose the only action you are capable of doing is grasping, and the only oppositions you can form are: palm opposition, pad opposition, and side opposition. Assume the inputs can be identified by the firing rates of three 'visual' neurons and your postures as the firing rates of three motor neurons. We can represent the three input objects as transposed vectors:

mug = [0.6, 0, 0.8]
pen = [0, 1, 0]
key = [0.8, 0, -0.6]

And the outputs as:

palm = [1, 2, 3]
pad = [0, 5, 4]
side = [1, 0, 0]

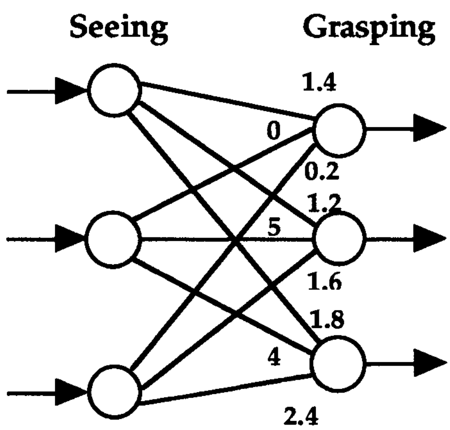

Figure C.9 Heteroassociative memory (of linear units) that associates patterns impinging on seeing receptors to patterns of motor activity for grasping. The set of weights learned for the three objects in the example are seen.

In order to associate a word that you see (the inputs) with one of the postures you can form (the outputs), you would need a set of weights on the connecting network as seen in Figure C.9. If the object 'key' was seen by this network, it would compute what posture to form as follows:

$$\begin{bmatrix} 1.4 & 0 & 0.2 \\ 1.2 & 5 & 1.6 \\ 1.8 & 4 & 2.4 \end{bmatrix} \begin{bmatrix} 0.8 \\ 0 \\ -0.6 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \tag{18}$$

From our list of vectors representing firing rates of the output neurons, we see that this is side opposition. The reader can check to see that the other input patterns will produce the desired output patterns. These input patterns were chosen because the vectors are orthonormal. Vectors that are orthogonal have a dot product equal to zero. Orthonormal vectors are orthogonal and also have a magnitude of 1. We can see that the number of stimulus/response vector pairs is limited by the size of the weight matrix. Nonlinear networks are more powerful, robust, and don't have the orthonormal constraint.

C.5 Summary

The power of a computational model using a neural network architecture is that the model can generalize from a few sample points. With a distributed representation, graceful degradation can occur; as well, local computations can be performed.

Adaptive models can learn. Using supervised learning, it would be similar to a child learning to grasp: the first time the child tries to grasp a heavy toy, some posture is chosen, and the toy drops from her hand. Failure in the task tells the brain that parameters, such as muscle set or the chosen posture, were chosen incorrectly, and adjustments are made so that success is more likely the next time. Modification can be made to either the parameter values or to the selection of the parameters; e.g., using more fingers to provide more force, or realizing that the texture of the object surface is important in choosing a grasp. Repeated trials allow the correct setting of parameters, until a successful grasp is selected, and even generalized from. This allows the child to eventually start picking up objects that she has never intereacted with before.

Artificial neural networks can be trained on real-world examples, and then they can generalize to solving arbitrary instances within their problem space. In adaptive neural nets, invariances can be learned, and encoded within the network, both in its topology and within the strengths of synaptic connections between the neurons. Other types of computations neural networks can perform include error correction, pattern analysis, and data reconstruction. Relationships between discrete or continuous-valued inputs and outputs can be determined; such a mapping can be an abstract spatial, functional, or temporal one.

In order to build a computational model using a neural network architecture, decisions have to be made about the types of processing units (McCulloch-Pitts or leaky integrators), their state of activation (continuous or discrete), what output function to use, the pattern of connectivity (feedforward or recurrent; number of layers), type of information coding, what propagation rule to use, what activation rule to use (linear or logistic), what learning rule to use (if adaptive), and the environment. Most commonly used in the literature today are feedforward, numerical mapping, gradient descent-trained networks. This is because: 1) most computational problems can be phrased as mappings from one real-valued array to another; 2) it is often the case that the problem is posed as a set of sample values and solutions (rather than as an algorithm); 3) feedforward networks are the most easily understood and trained; and 4) gradient descent is a very general, iterative optimization process.

While no one claims that the various algorithms, learning rules, assumptions, and simplifications used in artificial neural networks are biologically plausible, the argument for exploring such computations is that they are neurally-inspired. In the long run, they have much more potential for providing an understanding of the fundamental processing going on in the central nervous system than does the conventional computer metaphor (of static memory, separate from processing) that has existed for the last 40 years.

Appendix D. Prosthetic and Robotic Hands

"..the ideal prosthesis would serve its wearer as a natural extension of his human system."

--Mann (1974)

D.1 Introduction

The complex nature of the human hand, under the control of the central nervous system, is only highlighted by the loss of that hand, and the amputee looks to engineers for a prosthetic device that captures the beauty and versatility of the original hand. "Hands have their gifts inscribed in their very shape and design... the mind makes the hand, the hand makes the mind" (Focillon, 1947). Sterling Bunnell (1944) stated that "Our hands become extensions of the intellect." When people lose a hand, they are losing an intimate partner of their minds that combines fine coordinated movement, tactile sensation, proprioceptive feedback, expression and aesthetic appearance.

For centuries, engineers have attempted to reproduce this amazing human structure. The first recorded instance of an artificial hand was in 200 B.C. when a Roman general lost his hand during a war and was fitted with an iron hand. In modern times, the split hook was developed in the 1890's by D.W. Dorrance. An effective terminal device, the split hook controlled by a body-powered shoulder harness. Use of electrical energy in prosthetic hands was described by Borchard et al. (1919), although it was not usable with the available batteries. In this electromagnetically powered hand, the index and middle fingers pushed against the thumb. World War II spurned a national treatment program by the U.S. armed forces medical arms and a national research program to improve prostheses. The electrically powered Vaduz hand, patented in 1949, used the circumferential difference between a contracted and released muscle. The first artificial hand controlled by EMG was developed in Russia by Kobrinski et al. (1960). During the 1960's, the goal of Otto Bock Orthopedic Industries was to develop an electromechanically driven prosthetic hand that was functional and cosmetic. In 1965, they developed a hand that could grip using a thumb, index, and middle fingers.

In the 1980's and 90's, high-tech solutions are emerging to use new materials and miniaturized components, while attempting to satisfy active life-styles of the differently abled. Reduced voltage requirements, battery saving features, light weight alloys, modular designs, use of reinforced silicones for cosmetic gloves, and space age miniaturized motors and circuits have led to light weight, electrically powered prosthetic hands for adults and children. Users can comfortably wear these during an eight hour day. However, Baumgartner (1981) argued that no upper limb prosthesis will be able to do everything a hand does. He suggested that the functional prosthesis must be compared to a tool rather than to the human hand. As it is, tools already seem to be treated as an extension of the human arm (see Law, 1981). Proprioception of joint angles, muscle length, and muscle force seems to be extended to include clubs and tools.

A parallel engineering problem has been the development of functional end effectors for robots. Early robot end effectors, built and designed in the 1960's and 1970's, were simple two fingered grippers. Much like the split hook, these have only one degree of freedom. More recently, multi-fingered hands have been developed, such as the three fingered Stanford/JPL hand (Salisbury, 1985), the four fingered Belgrade/USC hand (Bekey, Tomovic, & Zeljkovic, 1990), and the five fingered Utah/MIT hand (Jacobsen, Iversen, Knuti, Johnson, & Biggers, 1986). Besides more fingers and thus more degrees of freedom, these devices are equipped with various sensors, such as tactile, force, pressure, slip, and joint sensors.

Besides the difficult mechanical problems of actuator design and packaging, a major stumbling block in both prosthetic and robot hand development is the control problem of coordinating and controlling multiple degrees of freedom when interacting with the environment. Adding more degrees of freedom complicates the control equations. Reducing the number makes the equations simpler but at the expense of versatility. Adding sensors provides the opportunity for triggered responses and feedback control, creating the problem of transducing sensory information accurately. The control problem in prosthetics takes on the additional complexity of identifying control sites. When a human hand is amputated, lost are all the intrinsic and many or most of the extrinsic muscles in the forearm (see Appendix A). So, even though a prosthetic hand might some day be built that parallels the appproximately 27 degrees of freedom of the human hand, a method for actuating those degrees of freedom must also be developed.

Prosthetic and robot hand designs provide a unique opportunity for understanding prehension. As alluded to in Figure 1.2, these devices and their controllers provide a realized or implemented model. Whether the hand to be driven is a mechanical hand or a human one, certain restrictions apply, particularly at the physical level in terms of dynamics and kinematics, even though they are different realizations (see Chapter 8). While a robot controller will not necessarily use the same algorithms that the central nervous system does (since we don't know those!), behaviors can be modelled and tested on a mechanical hand, with success or failure being seen immediately. High level control variables, such as opposition space parameters, could be used to drive the artificial device. Such an abstraction at the functional level is typical of the general progression toward machine-independence seen in computer systems, and would allow a variety of hand designs to be developed for different purposes but still be able to share a common control language.

D.2 Prostheses and Their Control

Objectives for the design of future prosthetic devices (Childress, 1974) include subconscious control, comfort, cosmetics, reliability, esthetics, and improvement over existing prosthetic devices. The control system should be (Jacobsen et al., 1982) reasonable to learn, natural, graceful, reliable, flexible, and include feedback. In terms of the fingers themselves (Law 1981), they should be light, robust, have consistent joint frictional forces, be compatible with socket and palmar materials, and provide an accurate fill for the cosmetic covering, maintaining a good cosmetic profile throughout the full range of movement. The needs of the amputee have been divided into two basic requirements: the desire for the best aesthetic replacement, and the restoration of specific hand functions (Baumgartner, 1981, Peizer, 1981). Currently, no one prosthetic device can accomplish all of these. The devices available include body-powered split hook or hand, electrically powered hand controlled by myoelectrically, and cosmetic passive hand. Studies have shown that amputees have a variety of functional needs (c.f., Millstein et al., 1986), and thus they may have one or more devices. In fact, Therapeutic Recreation Systems (Boulder, Colorado) has introduced a family of designs called the Super Sport series, shaped specifically just for catching a ball.

D.2.1 Control of prosthetic devices

Body powered prostheses use power transmitted in the most direct way for maximum indirect sensory feedback. Four different body sources are used (Baumgartner, 1981): the wrist joint, the forearm, biceps, and shoulder and thoracic muscles. Using the shoulder and thoracic muscles, force is transmitted by a shoulder harness and cable to the terminal device. Body-powered devices are relatively inexpensive, functional, reliable, and have some indirect sensory proprioceptive feedback (Muilenburg & LeBlanc, 1989). They are functionally better than other methods, because position and force feedback is available from the harness. The indirect sensory feedback is provided through extended physiological proprioception (Law, 1981), which comes from proprioceptive information about limb position and velocity. This seems to extend to include additional limb segments provided a consistent relationship exists between the position and velocity of the artifical segment and the position, velocity, and applied force of the contiguous natural body part (Law, 1981).

Externally powered, myoelectric prostheses are controlled by electromyographic (EMG) signals, where the force developed by the muscle is used to drive motors or to set control switches. Conventional myoelectric hands have a single channel from a pair of opposing muscle groups, controlling a single degree of freedom in the hand (Kyberd et al., 1987). The input is usually a simple on/off signal, where flexor tension opens the hand and extensor tension closes it. Depending on the level of the amputation, muscles use include forearm muscles, or biceps and triceps. Sensory information may come from visual and auditory cues, such as the sound of motors, motor vibration, accurate memory of opening-closing time, and movements of the center of gravity (Law, 1981).

Myoelectric digital on/off control uses a simple EMG threshold detect to control a switch. When muscle tension reaches a critical level, it causes the switch to change states, which in turn controls a motor to direct the hand in one direction or the other. Pinch force between finger can be indirectly related to the duration of the signal; the longer the closing motor runs, the harder the fingers pinch. Proportional myoelectric control is an alternative method of control. Integrated EMG amplitude varies closely with actual tension generated by muscle (see Sears & Shaperman, 1991). The EMG controls the motor directly, designed so that the output of the motor is proportional to the output of the muscle. With more muscle contraction, the faster the motor operates. The user has more sensitive slow and fast control of the hand, depending on the strength of the muscle contraction.

Myoelectric devices have certain advantages (Baumgartner, 1981), including no body harness, increased comfort, and more independent control in bilateral amputations. The disadvantages are that they not designed for heavy work, their weight is greater, costs are higher, and greater servicing is required. Most important however is the lack of sensory feedback, other than auditory and visual clues, requiring a high level of concentration. Proportional myoelectric control have additional advantages over digial myoelectric control, and these include better control of force and speed, and less muscular effort expended. A disadvantage of proportional myoelectric control is that currently the circuits are larger. However, it operates on a very low threshold EMG signal, and therefore operates with less muscle effort and continues to run until the muscles are completely relaxed.

Stein and Walley (1983) found that tasks with a myoelectric prosthesis took twice as long as a hook and five times as long as with a normal hand. Yet 60% of below-elbow amputees preferred to use the myoelectric prosthesis compared to a conventional prosthesis. Yet, although the subjects were able to accomplish the tasks faster with the hook vs the hand, extreme body movements had to be used due to the harnessing, such as rotating the trunk in order to rotate a heavy object. With the myoelectric prosthesis users, this was not observed.

However, in a survey of 33 patients on proportional versus digital control, Sears and Shaperman (1991) found the proportional myoelectric hand to be quicker than a hook and digital myoelectric hand, with the amount of effort reduced. Patients rated it low for its weight and bulkiness, but felt that it appeared more natural during use. Former digital hand wearers gave the proportional myoelectric hand the highest performance ratings, but the lowest rating on convenience. Since the user can control speed and force, it was felt that there was better control over fastenings in dressing, better dexterity in using pencil, better control in using tools, and noticed difference in ability to hold fragile objects.

Two other external control mechanisms have been used. One is servo-control, where the hand opening is proportional to a transducer's motion. The transducer is controlled mechanically, with very little froce and excursion. The other is switch control. It is similar to servo-control, in that some minimal force and excursion capability is required from a remaining body part. For example, a shoulder flexion of 1.3 cm excursion can be used to activate the switch (Peizer, 1981).

D.2.2 Split hook

As a prosthetic device, the split hook is strong, lightweight, simple, functional and reliable (Law, 1981). It has functional shapes (narrow tips, flat gripping surfaces, specialized tool-holding grips),

Table D.1 Commercially available hooks. As body-powered devices with one degree of freedom, they can be opened or closed voluntary. They consist of two gripping surfaces, each work as a virtual finger. Together, they can act as a VF3 (from Iberall, Beattie & Bekey, in press; reprinted by permission).

Manufacturer and Name	Control	Opp	VF1	VF2	VF3
Hosmer Dorrance					
Standard hooks	voluntary opening	side	1	2	1 and 2
Sierra APRL hook	voluntary closing	side	1	2	1 and 2
Sierra 2-load hook	voluntary opening	side	1	2	1 and 2
Contourhook	voluntary opening	side	1	2	1 and 2
Synergistic Prehensor	myoelectric control	side	1	2	1 and 2
Hugh Steeper, Ltd.					
Carbon Fiber Gripper	voluntary opening	pad	1	2	1 and 2
Powered Gripper	myo. or switch	pad	1	2	1 and 2
Mauch					
Split Hook (University of Utah)	voluntary opening	side	1	2	tip 1 and 2
United States Manufacturing Co.					
Split Hook	voluntary opening	side	1	2	1 and 2

durability and simplicity, low cost, and low weight (Sears et al., 1989). Voluntary opening is used as a control mechanism for most hooks, so that hook opens when the user activates it, and it closes by use of a spring. Much of their simplicity is due to the fact that they have one degree of freedom. Studies have been done to determine the useful acceptance of prostheses. Millstein et al. (1986) studied 314 patients and found the advantages of using the cable-operated hook to include that they are good for manual skills, not easily damaged, designed for rugged conditions, and easy to clean. However, the hook lacked cosmetic appeal, and there was difficulty in stabilizing some objects due to the hook's shape and sometimes insufficient gripping force.

Table D.1, displaying a list of commercial hooks currently available, evaluates their functionality in opposition space terminology. Hooks are categorized as having a side opposition because the opposition is occurring transverse to the palm. Hooks are structured so that at the tips, a finer side opposition is available for fine precision grasping between tip one (VF1) and tip two (VF2). The hook becomes bowed more proximally, providing a wider opening for dealing with larger objects in a grasp between one (VF1) and two (VF2). In general, hooks do not have the surface area necessary for palm opposition, and their ability to pick up larger and irregularly shaped objects is limited. Using both fingers together, it is possible to create a virtual finger three (VF3) useful for lifting and carrying objects, such as suitcases, plastic bags, etc. Recall from Chapter 2 that since this virtual finger is opposing gravity, and not another virtual finger, it is designated a VF3.

Of these devices, the Contourhook (Hosmer Dorrance) is a body-powered device having a unique design that provides two neoprene covered curved fingers that can apply side opposition very much like the human thumb in opposition to the side of the index finger. Another unique device is the Utah Split hook (Mauch), which uses an improved design over the standard split hook for gripping shapes and surfaces. This device has wider gripping surfaces than normal, and a special interlocking knife grip. The outside surface of the tips is urethane-rubber-coated for better friction for grasping paper. Cable excursion remains constant over the full range of movement, due to the way the cable housing is attached directly to the terminal device. Side opposition is used between the two fingers, as in the Hosmer Dorrance devices. However, the Utah hook's interlocking knife grip allows objects to be held in a side opposition between the base of the two hooks, using the distal end of one of the hooks as a VF3 in opposition to the upward forces developed in cutting with the knife (Sears et al., 1989).

Table D.2 Commercially available mechanical hands As body-powered devices with one degree of freedom, they can be opened or closed voluntary. They consist of a thumb and four fingers (although in some only two fingers are active). The thumb is a virtual finger 1, and the fingers are virtual finger 2. The four fingers can act as a VF3. (T=thumb; I=index, M=middle, R=ring, L=little) (from Iberall, Beattie & Bekey, in press; reprinted by permission). (continued)

Manufacturer and Name	Control	Opp	VF1	VF2[1]	VF3
Hosmer Dorrance					
Dorrance Hands	voluntary opening	pad	T	I-M&R-L	I-M-R-L
APRL Hand	voluntary closing	pad	T	I-M&R-L	I-M-R-L
Sierra Hand	voluntary opening	pad	T	I-M-R-L	I-M-R-L
Becker Imperial Hand	voluntary opening	pad	T	I-M-R-L	I-M-R-L
Becker Lock Grip Hand	voluntary opening	pad	T	I-M-R-L	I-M-R-L
Becker Pylite Hand	voluntary opening	pad	T	I-M-R-L	I-M-R-L
Robin-Aids Mechincal Hand	voluntary opening	pad	T	I-M-R-L	I-M-R-L
Robin-Aids Soft Mechanic. Hand	voluntary opening	pad	T	I-M&R-L	I-M-R-L

[1]While all four fingers are present in these hands, not all four fingers are active in all of them. An ampersand is used for hands where the ring and little fingers are not active.

Table D.2 (continued) Commercially available mechanical hands As body-powered devices with one degree of freedom, they can be opened or closed voluntary. They consist of a thumb and four fingers (although in some only two fingers are active). The thumb is a virtual finger 1, and the fingers are virtual finger 2. The four fingers can act as a VF3. (T=thumb; I=index, M=middle, R=ring, L=little) (from Iberall, Beattie, & Bekey, in press; reprinted by permission).

Manufacturer and Name	Control	Opp	VF1	VF2[2]	VF3
New York University					
Number 1 Hand	voluntary opening	pad	T	I-M&R-L	I-M-R-L
United States Manufacturing Co.					
Adj. Mechanical Hard Hands	voluntary opening	pad	T	I-M-R-L	I-M-R-L
Mechanical Soft Hands	voluntary opening	pad	T	I-M&R-L	I-M-R-L
Hugh Steeper, Ltd.					
Mechanical hands	vol. open/closing	pad	T	I-M-R-L	I-M-R-L

D.2.3 Commercially available mechanical hands

Hands have a thumb and four fingers, although not all four are functional. They are covered with life-like cosmetic gloves that improve their appearance but diminish their versatility. Having one degree of freedom, these mechanical devices can be powered and controlled as voluntary opening or closing. Artificial hands are rarely used by bilateral amputees, because hooks are so much more functional (Wilson, 1989). Another disadvantage of hands is the bulk and weight (about 18 oz or more vs 3-4 oz for an aluminum hook, Sears et al., 1989). Without feedback, other than visual and auditory

[2]While all four fingers are present in these hands, not all four fingers are active in all of them. An ampersand is used for hands where the ring and little fingers are not active.

Sears et al., 1989). Without feedback, other than visual and auditory feedback, they are hard to use when the hand obscures the object from view. The hook, in contrast, does not interfere visually as much as an artificial hand does. In the Millstein et al. (1986) study, disadvantages for the cable-operated hand were its difficulty to operate, awkwardness, its heavy weight, lack of durability, and a weak grip. It was rated good as a cosmetic nonactive prosthesis.

Commercially available active mechanical hands are seen in see Table D.2. In some of these, only three fingers are active. The thumb, as VF1, acts against the index and middle fingers, which in turn work in tandem as VF2. The fingers and thumb come together in pad opposition in all of these devices. The passive ring and little fingers add minimally in prehension. All four fingers can be used as a VF3 in a hook grasp to carry a bag. An example of a mechanical hand is the Dorrance hand, which is a voluntary opening hand consisting of a thumb and index and middle fingers with adjustable closing force. The ring and little fingers don't move.

Another example is the APRL voluntary closing hand (Hosmer Dorrance Corporation). Similar to the Dorrance Hand, it also has a moveable thumb and two fingers, with two passive fingers. The thumb can be pre-positioned in one of two positions, thus permitting the handling of a wide variety of objects. Being a voluntary closing device, it is self-locking in any position.

The NYU Number 1 Child-sized Mechanical Hand, for children ages 2-7, has two fingers and a thumb that articulate at the metacarpophalangeal joints. The nonfunctional ring and fifth fingers are passively mobile, and it uses a voluntary-opening four-bar linkage mechanism for adjusting the opening size. The fingers lock in a closed position, but an emergency override releases the clutch when necessary.

D.2.4 Commercially available electrical hands

Electric hands have a thumb and two fingers. The ring and fifth finger are created by an inner glove which covers and protects the mechanical parts. They use a variety of control methods, as seen in Table D.3, to activate the two fingers and thumb, opening and closing with one degree of freedom. Table D.3 displays a list of commercial hands, categorized into the same categories as in Table 1. The thumb, as VF1, acts against the index and middle fingers, which in turn work in tandem as a VF2. The fingers and thumb come together in pad opposition in all of these devices. The ring and fifth act in a limited way to assist VF2. The active fingers, the index and middle fingers, can be used as a VF3 to carry some object in a hook grasp.

Table D.3 Commercially available electrical hands. Myoelectric control, switches, or servos are used to power the one degree of freedom. They consist of a thumb and two fingers (two more fingers are created by a glove). The thumb is a virtual finger 1, and the fingers are virtual finger 2. The two active fingers can act as a VF3. (T=thumb; I=index, M=middle, R=ring, L=little) (from Iberall, Beattie, & Bekey, in press; reprinted by permission).

Manufacturer and Name	Control	Opp	VF1	VF2[3]	VF3
Hugh Steeper, Ltd. Electric (MH101-MH110)	myo. or switch	pad	T	I-M(R-L)	I-M
Hugh Steeper, Ltd. Electric (MH151-MH160)	servo control	pad	T	I-M(R-L)	I-M
Otto Bock Electrohand 2000	myoelectric	pad	T	I-M(R-L)	I-M
Otto Bock System Electric Hands	myoelectric	pad	T	I-M(R-L)	I-M
Systemteknik AB 2" Electric Hand	myo. or switch	pad	T	I-M(R-L)	I-M
Variety Ability Sys, Inc. VASI Hands	myo. or switch	pad	T	I-M(R-L)	I-M

Hugh Steeper Ltd. manufacturers the Steeper Electric Hand in four different sized hands for children and adults. They can be controlled either by switch, myoelectric control or servo-controlled. In contrast to a normal human hand, the thumb moves in same plane as two opposing fingers. In the human hand, the thumb travels in a plane at almost right angles to fingers. The thumb and first two fingers

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[3] Fingers in parentheses are not part of the hand itself, but are provided by the glove.

are active, while the other two are passive. The thumb and fingers are opened using a worm nut, which has the advantage that it cannot be driven backwards; thus, it retains its exact position unless the motor is activated. When the load goes above a maximum pinch force, the thumb releases. Steeper includes a battery saver mechanism in the controller, which senses the maximum opening mechanically and a preset pinch force electrically.

The Otto Bock System Electric Hand (Minneapolis, Minn.) has an automatic gear that ensures that capturing an object takes place at the maximum speed. When a maximum grip force is obtained, the gear changes to a higher gear reduction, and the grip force increases at a lower speed. This allows the user to increase the grip force until the required force is achieved. In order to reduce its weight, it has a removable battery that can be clipped to the patient's clothing.

The Systemteknik myoelectric hand, from Systemteknik AB of Stockholm (distributed by Liberty Mutual), comes in two sizes: one for children 2-6 years of age, and a larger hand for children 5-9 years of age. A clutch permits slippage when a strong opening force is detected. The user stops the motor when the desired pinch force is reached, since the hand will maintain a force indefinitely until it is opened voluntarily.

D.2.5 Commercially available specialized devices: neither split hook nor hand

Specialized devices have been developed for activites relating to sports, recreation, and work. In addition, general purpose devices have been designed to take the place of the hand and hook. Passive devices include a knife, fork, spoon, hooks, hammer, typewriter key push, automobile steering wheel appliance, kitchen appliances, nail brush holder, garden tool holders, and fishing rod holders (Law, 1981). Active devices include include pliers, tweezers, tool holders and general devices, such as the CAPP 2 and the Otto Bock Greifer (see Table D.4). General non-standard devices are more cosmetically pleasing than split hooks and are usually more functional than hands. However, as with most other types of devices available, they have only one degree of freedom.

Table D.4 Commercially available non-standard devices. As body-powered devices with one degree of freedom, they can be opened or closed voluntary. They consist of two gripping surfaces, each work as a virtual finger. Together, they can act as a VF3 (from Iberall, Beattie, & Bekey, in press; reprinted by permission).

Manufacturer and Name	Control	Opp	VF1	VF2	VF3
Hosmer Dorrance					
CAPP I	voluntary opening	pad	lower jaw	upper jaw	upper jaw
CAPP II	voluntary opening	pad	lower jaw	upper jaw	upper jaw
Otto Bock, Inc.					
System Elec. Greifer	myoelectric control	pad	left jaw	right jaw	left and right jaw
Therapeutic Recreation					
Grip Series	voluntary closing	pad	lower jaw	upper jaw	upper jaw
ADEPT Series	voluntary closing	pad	lower jaw	upper jaw	upper jaw

The UCLA Children's Amputee Prosthetic Program (CAPP) (Hosmer Dorrance Corporation) has produced functional non-hand, non-hook terminal devices that are not mechanical in appearance. CAPP I is for children up to ten years of age, while the CAPP II is for teenage and adult amputees. The CAPP II was designed to provide a general purpose device for unilateral amputees that performs functions usually carried out by the non-dominant hand (Shaperman & Setoguchi, 1989). CAPP II was designed to provide a secure grip on objects, ease of operation, a pleasing appearance, and reliable service for general purpose applications. Its wide palmar surface covered by a resilient Urethane cover allows a secure grasp on an object. An alternative to a hook and a hand, it is body-powered by a voluntary opening mechanism. The secure grip is provided by the combined action of a closing spring, a full frictional, resilient cover, and an automatic lock which prevents the device from opening further when outside forces act on the thumb. When the user places tension on the line, the lock releases; when tension is relaxed, the lock engages. The CAPP provides pad opposition, with VF1 being the lower thinner jaw and VF2 the upper larger jaw. A notch in the more proximal end of the larger jaw provides a way to turn the larger jaw into a VF3, one that opposes gravity in holding an object hooked in the notch.

Useful for more rugged activities, the Otto Bock System Electric Greifer has two equal sized thick jaws with small talons on the ends that can be adjusted in order to improve the angle of approach. These flat tip grasping surfaces of the tips remain parallel throughout range of opening and provide high pinch force for a secure grip (Sears et al., 1989). The System Electric Greifer has one degree of freedom. In terms of oppositions, it provides pad opposition, with VF1 being one jaw and VF2 being the other one. Using both jaws together as VF3, a suitcase can be carried.

TRS (Boulder, Colorado) has a family of designs that are neither in the shape of split hooks or hands. In all these devices, two rounded and scalloped virtual fingers provide either pad opposition. Children are capable of gripping as hard or harder than with their natural hands. Tasks they can do include swinging, climbing, riding a bike, tie shoes, swing a bat, etc. The upper jaw hooks around so that it can be used as a VF3.

D.2.6 Research examples

Table D.5 provides a list of hands currently being developed at several universities and laboratories.

Kenworthy (1974) developed a design for a hand that is based on an observation that in the normal hand, the fingers exhibit a low level of mobility in comparison to the thumb. His design allowed objects, such as pens and utensils. The index and middle fingers were constructed in the form of a rigid hook, while the ring and little fingers were cosmetic only. Three point contact was achieved using the thumb, middle, and index fingers, with the middle finger slightly more flexed than the index finger. A fourth contact point could occur on the proximal phalanx of the index finger, thus creating the writing or external precision grip, as described in Chapter 2. The fingers themselves did not move, while thumb movement occurred in a plane perpendicular to the fingers. External precision is a combination of pad and side opposition, where pad opposition occurs between the thumb (VF1) and index finger (VF2), while side opposition occurs

Table D.5. Research prosthetic hands. Body-power, myoelectric control, switches, or servos are used to power these devices. They consist of a thumb and two or four fingers. The Stanford University devices have two jaws. The thumb (or jaw) is a virtual finger 1, and the fingers (or jaw) are virtual finger 2. Active fingers or jaws can act as a VF3. The cutout in Prehensor A can also be a VF3. (T=thumb; I=index, M=middle, R=ring, L=little) (from Iberall, Beattie & Bekey, in press; reprinted by permission).

Organization and Name	Control	Opp	VF1	VF2[4]	VF3
P.M.R. Orthopaedic Hosp., Edinburgh					
Kenworthy Hand	body or ext.	pad	T	I-M(R-L)	
		pad& side	T	I/M	radial side of palm
					I-M
Southampton University					
Southampton Hand	myoelec.	pad	T	I	
		pad	T	I-M-R-L	
		palm	palm	T-I-M-R-L	
		palm& side	palm/T	I-M-R-L/I	
		side	T	I	
					I-M-R-L
Stanford University					
Prehensor A	vol. closing	pad	lower jaw	upper jaw	cutout
					upper jaw
Prehensor C	vol. closing	pad	left jaw	middle jaw	
		pad	middle jaw	right jaw	
					left and middle; right
Prehensor B	vol. closing	side	thinner jaw	thicker jaw	

[4]Slash separates the use of real fingers in oppositions. Also, see Footnote for Table 3.

between the thumb (VF1) and middle finger (VF2). Having the extra contact point at the radial side of the palm (VF3) gives the hand the ability to use forks, knives and pens. For somewhat large objects, pad opposition occurred between the thumb (VF1) and the index and middle fingers (VF2). The ring and little fingers, formed by the glove, could slightly assist VF2. In addition, a hook grip could be formed using the active fingers as VF3. Interestingly, a 'powder grip' provided automatic adaptation to the shape of the gripped object. This was achieved using a non-stretch skin of cloth-reinforced PVC partially filled with glass beads, which deformed in a way to rigidly pack the beads, thus providing additional stability and padding.

Following experiments with sensor-based devices, the Southampton University hand (Chappell & Kyberd, 1991) was developed to create a prosthesis that has greater function and is hand-like in appearance and action. It has five functioning digits and four degrees of freedom. The index finger acts independently from the other three fingers, which move in tandem. The other two degrees of freedom are in the thumb. Three types of sensors are supported: force sensors tell the location of contact with the object; slip transducers indicate if the object is slipping from the grasp; and potentiometers in the proximal joints measure degree of flexion. Pad opposition can occur in two ways: first, between the thumb (VF1) and the index (VF2), and secondly, between the thumb (VF1) and all four fingers (VF2), although in both cases the thumb opposes the index and middle fingers. Palm opposition can also be selected. Here, the fingers (VF2) oppose the palm (VF1). If the object is small enough, the thumb will move around to the radial side of the index (thus combining side opposition with palm opposition). Otherwise, it will aid the fingers in opposing the palm. On contact, the controller applies a small load on the fingers. If the object begins to slip, tension is increased. This automatic response can be overriden by the user. Kyberd et al. (1987) have combined the use of tactile and slip sensory information with intelligent thumb positioning to simplify the control sites problem, and thus have created a powerful prosthetic hand with five different postures.

Meeks and LeBlanc (1988) studied three prototypes as possible designs for new prosthetic terminal devices. Prehensor A, developed from a study of human hands, uses a three-jaw chuck grasp and has many curvatures for multi-point contacts with objects. Providing pad opposition between two jaws, it has a cutout in the larger jaw that can act as a VF3 for grasping pens. Prehensor B was based on aesthetic considerations and has a rotary thumb. As it rotates, it provides side opposition either to the flat side or else to the more curved side of the larger jaw. Prehensor C was based on functional considerations, and has 3 jaws. Pad opposition can occur in two different ways: first, it can occur between small pads on the left (VF1) and middle jaw (VF2), and secondly, it can occur between the middle jaw (VF1) and the right jaw (VF2). Due to the bowed space between the jaws, this second way allows a cylindrical object, such as a soda can, to be grasped.

D.3 Dextrous Robot Hands

A simple two-fingered gripper is similar to a prosthetic split hook in that there is only one degree of freedom. As a functinal unit, it can grasp a variety of objects and it is easy to control. However, it is limited in the tasks that it can perform. One industrial solution has been to develop special purpose end effectors. The end of the manipulator is a uniform clamping mechanism, such as a bayonet mount or magnet, and devices that can be attached to this include powered screwdrivers, drills, paint cans, etc. When one task is finished, the computer replaces the current end-effector to some known location, and picks up another end-effector, specific to the task at hand. This is both costly and time-consuming.

An alternative has been to develop general purpose end-effectors, called dextrous robot hands. While these are also costly and still research tools, to date each device built has been designed specifically to study one aspect of grasping.

As mentioned in the introduction to this chapter, a major stumbling block is the control problem of coordinating multiple degrees of freedom in light of the complex interaction of forces in prehension. Adding more degrees of freedom complicates the standard control equations used today; reducing them makes the equations simpler but one loses versatility. One solution has been to add sensors to the hands. This causes its own problems, of course, in terms of physical layout, transducing mechanisms, and interpretation of the signals.

In the next sections, we describe various multi-fingered robot hands.

D.3.1 Stanford/JPL hand

The Stanford/JPL hand (see Figure D.1) was built by Ken Salisbury in 1982 with two requirements: 1) it should be able to exert arbitrary forces or impress arbitrary small motions on the grasped object when the joints are allowed to move; and 2) it should be able to constrain a grasped object totally by locking all the joints (Salisbury, 1985 or Salisbury & Craig, 1982).

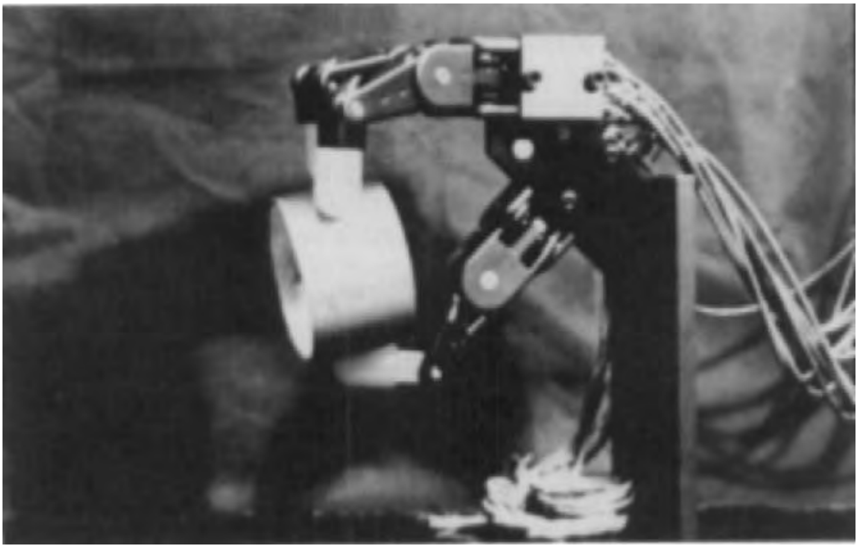

Figure D.1 The Stanford/JPL hand. It consists of three fingers, each of which has four degrees of freedom.

In determining a suitable design for the hand, only three fingered, three link per finger configurations were analyzed; an additional constraint on the choices were that all contacts allowed the same freedom of motion, ignoring zero and six DOF contacts. Other design parameters include link lengths, relative locations, joint limits, desired grip points, object sizes, kinematics. Using a program to help in the search for choosing parameter values based on maximizing performance criteria, the design seen in Figure D.1 was settled upon. The performance criteria were based on the working volume, mechanical design criteria, palm areas, ability to perform power grasp. It has three fingers, each having three degrees of freedom. Tendons are arranged in an n+1 arrangement, meaning that there is only one tendon that acts as an antagonist to the three tendons at the three joints. For positioning the fingers and using them to apply forces, Salisbury used stiffness control. By running the tendons past small strain gauges on cantilevers, tendon tension can be sensed. The relationship between a small change in tendon displacement ∂X and tendon tension F follows the mass-spring law, that is, $F=K\partial X$. Using an algorithm that displaces the tendon by a small amount, the tension on the tendons can be read from the strain gauges, since the stiffness K of the tendon is fixed. Sensing a small change in tension will provide the controller with knowledge about the change in tendon length.

This hand has been used in various systems, including Stansfield (1991).

D.3.2 Utah/MIT hand

The Utah/MIT hand (see Figure D.2), built by Steve Jacobsen and colleagues, has four fingers, with each having four DOFs (Jacobsen, Iversen, Knuti, Johnson, and Biggers 1986). Control of its 16 degrees of freedom is performed at a 'high' level in the computer.

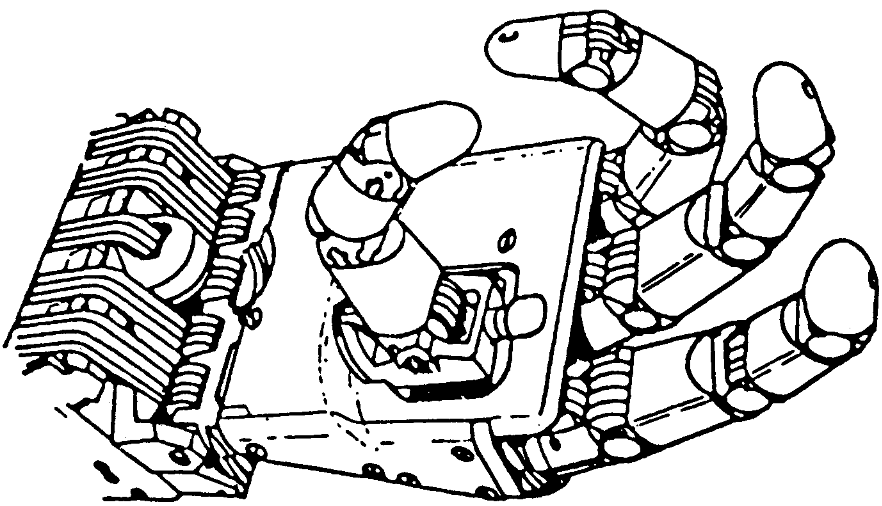

Figure D.2 The Utah/MIT hand. It consists of three fingers and one thumb, each of which has four degrees of freedom (from Jacobsen et al., 1986; reprinted by permission).

D.3.3 Belgrade/USC hand

The Belgrade/USC hand (see Figure D.3), with its five fingers, was built by Rajko Tomovic and colleagues (Bekey, Tomovic, & Zeljkovic, 1990). It has four independent degrees of freedom, and uses reflex control. The motions of the three joints are not individually controllable; they are connected by linkages in order to move similarly to human fingers during grasping as the fingers flex (a virtual). The thumb is articulated with two coupled joints, and capable of rotation about an axis normal to the palm, to bring it into opposition with any of the other s. A unique feature of the hand is its autonomous shape adaptation. Four motors are mounted in the wrist structure to provide the external degrees of freedom. Two motors move the thumb, while the others move two fingers each as a virtual finger. The virtual finger drive is applied to each pair of fingers through a lever structure, such that if the motion of one real finger is inhibited, the second can continue to move, thus achieving shape adaptation without external control (Bekey et al., 1990; Tomovic, Bekey, Karplus, 1987). The consequence of this design is that the hand is well suited to autonomous grasping of objects of arbitrary shape; it is capable of preshaping; and is simple to control, since all the motors are located in the wrist structure. Touch sensors are located on the finger tips and on the palm, position sensors are embedded within the fingers. The hand is mounted on a Puma 560 robot.

The idea is to reduce the enormous number of possible degrees of freedom of multied hands to a small number of 'standard' configurations for grasping tasks. A set of eight grasp modes was developed (Liu and Bekey, 1986), based on the typical use of robot hands in industrial settings. These postures, as was seen in Table 2.1, include the lateral pinch, power grasp, span, precision pinch, etc. The underlying control philosophy for grasp execution is based on a shape adaptive principle. Finger positions adapt to the shape of the object and grasp force is appropriate to its weight and surface friction characteristics. In contrast with the approach taken in the Utah/MIT hand, Tomovic and Bekey believe that this aspect of control should be built into the hand itself, using contact, pressure and slip sensors. An earlier version of such a shape adaptive hand was built some 25 years ago for prosthetic purposes (Tomovic & Boni, 1962).

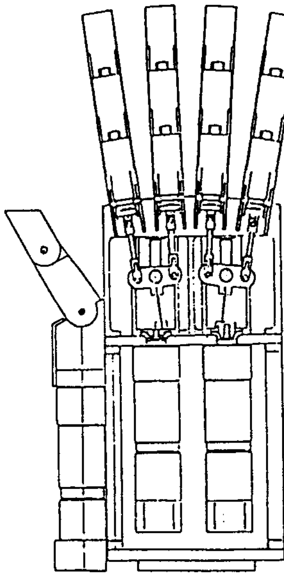

Figure D.3 The Belgrade/USC hand. It consists of four fingers and one thumb. The four fingers have one degree of freedom generated from three coupled degrees of freedom at the joints. The thumb has two degrees of freedom, allowing for flexion/extension and adduction/abduction (from Bekey et al., 1990; reprinted by permission).

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