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BIOMECHANICS AND CONTROL OF TORQUE PRODUCTION DURING PREHENSION

A Thesis in

Kinesiology

by

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ABSTRACT

The coordinated action of fingers during static tasks involving exertion of force and torque on a hand-held object was studied. Subjects were asked to keep a handle with an attachment that allowed for independent change of the suspended load (0.5-2.0 kg) and external torque (0.375-1.5 Nm) in a vertical position while applying minimal effort. Normal and shear forces were measured from the thumb; normal forces only were measured from the four fingers.

Experimental results: (1) The thumb shear force increased during supination efforts and decreased during pronation efforts. (2) The total moment of the normal finger forces counterbalanced only approximately 50% of the external torque. Hence, shear forces accounted for approximately one-half of the total torque exerted on the object. (3) The total normal force increased with external torque. The total force magnitude did not depend on the torque direction. (4) The forces of the 'peripheral' (index and little) fingers depended mainly on the torque while the forces of the 'central' (middle and ring) fingers depended both on the load and torque. (5) There was a monotonic relationship between the mechanical advantage of a finger (i.e., its moment arm during torque production) and the force produced by that finger. (6) Antagonist finger moments acting opposite to the intended direction of the total moment were always observed. At low external torques, the antagonist moments were as high as 40-60% of the agonist moments.

Modeling: A three-zone model of coordinated finger action is suggested. In the first zone of load/torque combinations, activation of antagonist fingers, i.e., fingers that

generate antagonist moments, is necessary to prevent slipping. In the second zone, the activity of agonist fingers is sufficient for preventing slips. In the third zone, the performer has freedom to choose between either activating the antagonist fingers or redistributing the forces amongst the agonist fingers.

Optimization: Optimization modeling was performed using as criteria the norms of (a) finger forces, (b) relative finger forces normalized with respect to the maximal forces measured in single-finger tasks, (c) relative finger forces normalized with respect to the maximal forces measured in a four-finger task, (d) relative finger forces normalized with respect to the maximal moments measured in single-finger tasks, and (e) relative finger forces normalized with respect to the maximal moments measured in a four-finger task. All five criteria failed to predict antagonist finger moments when these moments were not imposed by the task mechanics.

Reconstruction of neural commands: The vector of neural commands $[c]$ was reconstructed from the equation $[c] = [W]^{-1}[F]$, where $[W]$ is the finger interconnection weight matrix adjusted from Zatsiorsky *et al*. (1998) and $[F]$ is the vector of finger forces. The neural commands ranged from 0 (no voluntary force production) to 1 (maximal voluntary contraction). For fingers producing moments counteracting the external torque (‘agonist’ fingers), the intensity of the neural commands was well correlated with the relative finger forces normalized to the maximal forces in a four-finger task. When fingers worked to produce moments in the direction of the external torque (‘antagonist’ fingers), the relative finger forces were always larger than those expected from the intensity of the corresponding neural commands. The individual finger forces were decomposed into forces due to ‘direct’ commands and forces induced

by enslaving effects. Optimization of neural commands resulted in the best correspondence between the actual and predicted finger forces. The antagonist moments were, at least in part, due to enslaving effects: strong commands to agonist fingers also activated antagonist fingers.

Key words:

Hand · Fingers · Motor redundancy · Voluntary movement · Human

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DEDICATION

To the loving memory of my mother, Paula Gregory, who passed away during the writing of this dissertation.

CHAPTER 1

INTRODUCTION

The functions of the hand are numerous; the most important are the functions of touch (an ‘organ of information’; Tubiana, 1981) and prehension (an ‘organ of accomplishment’; Tubiana, 1981). We use our hands to perform a variety of other tasks that play an essential role in our lives, such as nutritional, expressive, sexual, hygienic, and thermoregulatory functions. Since we can perform such a remarkable array of functions with our hands, the question arises: How does our central nervous system (CNS) organize and control the tasks that we carry out with our hands?

The hand and wrist consist of 27 bones; there are 39 muscles located either in the forearm (extrinsic muscles) or in the hand itself (intrinsic muscles) that move the fingers and wrist (MacKenzie and Iberall, 1994; Tubiana, 1981). This creates a situation in which the number of muscles exceeds the number of degrees of freedom (DOFs) provided by the joints, resulting in a statically redundant and kinematically over-determined system. Originally, the DOFs problem was formulated with respect to the discrepancy between the number of kinematic DOFs of the body and the number of mechanical constraints imposed on the system. Saltzman (1979) described the DOFs of a system as “the least number of independent coordinates required to specify the position of the system elements without violating any geometrical constraints.” The concept of DOFs is not, however, specific to the kinematics of the body: it can exist at all levels of the movement production system, such as motor units, muscles, joints, etc. This issue of excessive DOFs is often referred to as the Bernstein problem: there are multiple solutions

to the control problem of performing a given task (Bernstein, 1967). Indeed, Bernstein viewed the main issue of motor control as the elimination of redundant DOFs.

The control of the hand can be considered as an example of how the CNS solves the motor redundancy problem. When a task is to produce a certain mechanical effect by activating several fingers, e.g., to generate a required force or torque, the effort can be distributed among the fingers in many different ways. Conceptually, this problem is similar to defining the force distribution among muscles serving a joint, which is often referred to as the force sharing (distribution) problem (Crowninshield and Brand, 1981b; Herzog, 2000).

Several methods are commonly used to analyze the force sharing problem: electromyography-to-force processing algorithms, optimization, and artificial neural networks (for reviews, see Herzog, 1996; van den Bogert, 1994; Zajac and Gordon, 1989). A general problem with these techniques is that they cannot be validated experimentally in man. Another approach to the redundancy problem is the direct measurement of muscle/tendon forces (for a review, see Gregor and Abelew, 1994). However, this method is problematic and difficult to perform in human subjects. The study of force distribution among fingers is advantageous when analyzing the motor redundancy problem because the forces produced by the individual fingers can be directly measured and the force sharing pattern can easily be determined. Consequently, this allows models and hypotheses to be validated.

Numerous studies have examined the distribution of grasp forces between the four digits opposing the thumb (Amis, 1987; Hazelton *et al*., 1975; Kinoshita *et al*., 1995, 1996a, b; Li *et al*., 1998a, 2002; Ohtsuki, 1981; Radhakrishnan and Nagaravindra, 1993;

Radwin *et al*., 1992; Reilmann *et al.*, 2001; Talsania and Kozin, 1998). The following three main phenomena have been observed during gripping and pressing tasks: (a) *force sharing* – the total force produced by all the involved fingers is shared among the fingers in a specific manner (Amis, 1987; Radwin *et al*., 1992; Kinoshita *et al*., 1995; Li *et al*., 1998a, b; Reilmann *et al.*, 2001); (b) *force deficit* – the force produced by a given finger in a multi-finger task is smaller than the force generated by this finger in a single-finger task (Ohtsuki, 1981; Kinoshita *et al*., 1996; Li *et al*., 1998a, b, 2001); and (c) *enslaving* – the fingers that are not required to produce any force by instruction are involuntarily activated (Hager-Ross and Schieber, 2000; Kilbreath and Gandevia, 1994; Latash *et al*., 1998; Li *et al*., 1998a, b; Zatsiorsky *et al*., 1998, 2000). Enslaving effects reveal the existing biomechanical and neurophysiological interconnections among the fingers: a neural command to one finger induces activation of other fingers (cf. Schieber, 1991, 1996; Häger-Ross and Schieber, 2000).

In pressing and gripping tasks described above, the fingers act simply as agonists, i.e., the mechanical effects of their actions are simply summed up. However, in prehension tasks requiring the simultaneous exertion of force and torque on a hand-held object, the control of the fingers is much more complex. When manipulating a hand-held object, for instance when drinking from a glass, one needs to apply sufficient grip force to prevent the object from slipping out of the hand. In addition, one needs to control the total torque exerted on the glass such that the glass remains vertical (in this case the torque magnitude should equal zero) or at a controlled angle that is suitable for drinking and preventing the liquid from being spilled. Usually, the requirements for grip force stabilization allow for some laxity, while the requirements for total torque production are

highly specified. As in the example of drinking from a glass, the grip force needs only to be larger than the slip threshold and smaller than the force that would break the object. In contrast, the torque applied to the glass needs to be precisely controlled since any error will lead to rotation of the glass and spilling of the liquid.

During manipulation of the glass, the fingers may act as force agonists and torque antagonists. To prevent the glass from slipping, the fingers act as agonists; each of them contributes to the total grip force. In contrast, the index and middle fingers and the ring and little fingers exert moments of force in opposite directions about an axis of rotation created by the thumb. These two pairs of fingers are torque antagonists. To minimize the total finger force, the fingers that generate a moment opposite to the intended moment should not produce any force. At the same time, to prevent the object from slipping they may be required to generate a force that contributes to the total grip force. The CNS must somehow find a balance between these conflicting requirements.

Investigations on torque production during grasping tasks are few in number. In the majority of these experiments subjects grasped objects with the tips of the index finger and thumb only (Goodwin *et al*., 1998; Jenmalm *et al*., 2000; Johansson *et al*., 1999; Kinoshita *et al*., 1997; Salimi *et al*., 2000). Force sharing, the distribution of the total force produced among the fingers involved in a task, was not discussed in these experiments. In a recent experiment performed by Santello and Soechting (2000) subjects were asked to hold a handle for 30 s. In different trials, the location of the center of mass of the handle was changed; this caused the external torque to vary. The study focused mainly on the continuous oscillations of the individual finger forces during the holding period. It was demonstrated that, in all frequency bands, the oscillations of the

different finger forces were synchronous and, hence, determined by a multi-finger synergy.

1.1 PROBLEM STATEMENT

The purpose of this study was to investigate the forces exerted by five digits on a hand-held object during static force and torque production tasks. In addition, the strategies used by the CNS to fulfill the apparently conflicting force and torque production requirements were examined. A prismatic precision grip was utilized in this study, i.e., a grip configuration in which the tips of the fingers and thumb oppose each other (Cutkosky and Howe, 1990). Subjects were required to stabilize a handle with an attachment that allowed for independent changes of the suspended load (0.5-2.0 kg) and external torque (0.375-1.5 Nm) in a vertical position while applying minimal effort (as subjectively assessed by the individual subjects). Normal and shear forces were measured from the thumb; normal forces only were measured from the four fingers.

The specific purposes of this study were to acquire information concerning:

(1) the forces and moments produced by the individual fingers during static force and torque production tasks;

(2) to develop a biomechanical model of coordinated finger action during static tasks involving exertion of force and torque on a hand-held object; and

(3) to develop optimization and neural network models to examine the strategies used by the CNS during static force and torque production tasks.

The independent variables in this experiment were:

(1) The magnitude of the external load. The mass of the loads suspended from the experimental apparatus ranged from 0.5 to 2.0 kg in 0.5 kg increments.

(2) The magnitude of the external torque. The torques created as a result of the external loads suspended from the handle/beam apparatus ranged from 0 to 1.5 Nm in 0.375 Nm increments. Torques were created in both clockwise (CW) and counterclockwise (CCW) directions by varying the placement of the external load with respect to the handle of the experimental apparatus.

The dependent variables in this experiment were:

(1) The total normal force and individual normal forces produced by the index, middle, ring, and little fingers, as well as the thumb normal and shear forces.

(2) The slip force, the minimal grasp force that is necessary to prevent an object from slipping out of the hand.

(3) The safety margin, the ratio of the excess grip force to the minimum grip force that just prevents slipping.

(4) The force sharing value, the percentage of the normal force produced by an individual finger relative to the total normal force generated by all four fingers.

(5) The force actualization value, the percentage of the normal force produced by an individual finger relative to the maximal normal force generated by that finger in either single-finger or four-finger tasks.

(6) The total moment and individual moments produced by the index, middle, ring, and little fingers with respect to the pivot point of the center of the thumb transducer.

(7) The position of the neutral line, the distance from the point of application of the resultant force to the center of the thumb transducer.

(8) The agonist and antagonist moments produced by the agonist and antagonist fingers, respectively, as well as the antagonist/agonist moment ratio.

1.2 HYPOTHESES

It was hypothesized that:

(1) The individual finger forces, force sharing patterns, and force actualization values are scaled in proportion to the external load and torque.

(2) The individual finger forces, force sharing patterns, and force actualization values are scaled in proportion to the finger moment arms with respect to the axis of rotation.

(3) Subjects produce optimal finger forces and force sharing patterns during static force and torque production tasks. [Note: optimal finger forces are those that result in only mechanically necessary antagonist moments]

(4) The neural network developed in this study will account for force sharing and enslaving and be able to predict individual finger forces and force sharing patterns during torque production tasks.

1.3 DEFINITIONS

Agonist – a finger that produces a moment of force that counteracts the external torque; an agonist moment is a moment of force in the intended direction of the total moment.

Antagonist – a finger that produces a moment of force in the direction of the external torque; an antagonist moment is a moment of force in the opposite direction of the total moment.

Central (neural) command – a measure of the central neural drive; a neural parameter (something that we do not know) that assumes a maximal value (1) when maximal voluntary contraction is required and a minimal value (0) when voluntary force is not produced (Zatsiorsky et al., 1998).

Enslaving – involuntary activation of the fingers that are not required to produce any force by instruction in a task (Zatsiorsky *et al*., 1998, 2000).

External torque – the moment of force generated by the external load

Force deficit – the difference between the maximal force produced by a given finger in single-finger and multi-finger tasks (Li *et al*., 1998a, b).

Force sharing – the distribution of the total force produced among the fingers involved in a task (Li *et al*., 1998a, b).

Grip force – the force generated between the contact points of the hand and a grasped object that acts to keep the object in the hand (Wing *et al*., 1996).

Load force – the resultant or net force acting on an object; usually excludes grip force (Wing *et al*., 1996).

Moment – the moment of force exerted by a finger force(s) about a pivot point at the center of the thumb transducer.

Neutral line - the moment arm of the total force produced by all four fingers in combination, i.e., the distance from the point of application of the resultant force to the center of the thumb transducer.

Normal force – the force produced by a digit perpendicular to the grasping surface of the experimental apparatus.

Precision grip – a grip in which the object is grasped by the tip of the thumb opposing the tip of one or more fingers (Wing *et al*., 1996).

Safety margin – the grip force applied to an object in excess of that required to oppose the load force and prevent the object from slipping (Westling and Johansson, 1984).

Shear force – the force produced by a finger or thumb parallel to the grasping surface of the experimental apparatus.

Slip force – the minimal grip force that is necessary to prevent an object from slipping out of the hand (Johansson and Westling, 1984).

Static – the forces acting on a system are balanced and hence the system is not accelerating; the system is either stationary or moving at a constant velocity.

Torque – the total torque exerted on the handle by the subject; it is equal to the external torque but opposite in direction

1.4 ASSUMPTIONS AND LIMITATIONS

(1) Only 18 healthy males in the 20-30 year age range participated in this study. The sample may not represent the larger population.

(2) Only the dominant hand was used to perform static force and torque production tasks; the non-dominant hand was not an object of the analysis.

(3) The external torques experienced by the subjects were not normalized relative to the maximal torque production potential of each individual participant.

(4) The location of the force transducers on the handle of the experimental apparatus was the same for all subjects; the positions of the transducers were not adjusted to account for individual differences in hand size. Participants with very large or small hands were excluded from the study.

(5) The location of the force transducers on the handle of the experimental apparatus constrained the position of the fingertips to a vertically straight line, which is unnatural for precision grip.

(6) Only the normal forces (perpendicular to the grasping surface of the experimental apparatus) produced by the fingers were measured; no shear forces were recorded.

(7) It was assumed that the contact points between the digits and the force transducers were located at the center of the transducers. It is possible that these contact points displace during multi-finger prehension involving torque production (Li, 2002).

(8) It was assumed that the subjects were using the minimal total force necessary to stabilize the handle/beam apparatus in a state of static equilibrium.

1.5 SIGNIFICANCE

The present study was the first to systematically examine the forces exerted by five digits on a hand-held object during static force and torque production tasks. In addition, this study addressed the strategies used by the CNS to fulfill the apparently conflicting force and torque production requirements. Information concerning the individual finger force control during force and torque production tasks is of great value for designing hand prostheses (Crago *et al.*, 1996; MacKenzie and Iberall, 1994), dextrous robotic hands (MacKenzie and Iberall, 1994; Mason and Salisbury, 1985; Venkataraman and Iberall, 1990), and hand-held tools and work equipment (Buchholz and Armstrong, 1992; Chaffin *et al*., 1999; Sommerich *et al*., 1998). Such data is also useful when evaluating abnormal hand function (Brand and Hollister, 1999; Chao *et al*., 1989; Schuind *et al*., 1994) and understanding the neural mechanisms that control prehensile behavior (Lemon, 1999).

CHAPTER 2

REVIEW OF LITERATURE

Following an introductory section defining prehension and describing patterns of prehensile hand function, this chapter will provide a review of the anatomy, biomechanics, and control of the human hand. The chapter will conclude with a discussion of the motor redundancy problem and force sharing among synergistic muscles.

2.1. PREHENSION

Prehensile movements of the hand are those in which an object is seized and held partly or wholly within the compass of the hand for a purpose such as manipulating, transporting, or feeling the object (Barr and Bear-Lehman, 2001). MacKenzie and Iberall (1994) provide an alternative definition of prehension: the application of functionally effective forces by the hand to an object for a task, given numerous constraints. These constraints include both physical and functional constraints. Physical constraints include the properties of the arm and hand, gravitational and frictional forces, and the properties of the object such as surface compliance, shape, texture, temperature, size, etc. (MacKenzie and Iberall, 1994). The functional constraints of prehension can be summarized as follows (MacKenzie and Iberall, 1994): (1) apply forces to match the anticipated forces in the task; (2) impart motion to the object (manipulate) or transport the object as necessary; and (3) gather sensory information about the state of the interaction with the object during the task in order to ensure grasping and manipulative stability.

Efficient prehensile function of the hand depends on a large number of factors, the most important of which are (Barr and Bear-Lehman, 2001): (1) mobility of the first carpometacarpal (CMC) joint and, to a lesser extent, the fourth and fifth metacarpophalangeal (MCP) joints; (2) relative rigidity of the second and third CMC joints; 3) stability of the longitudinal finger and thumb arches; (4) balanced agonist and antagonist activity between the intrinsic and extrinsic hand muscles; (5) adequate sensory input from all areas of the hand; and (6) the precise relationships among the length, mobility, and position of each digital ray.

2.1.1. Patterns of Prehensile Hand Function

There are an infinite number of ways in which objects of varying shapes and sizes may be grasped. However, a broad classification system for grasp has evolved to identify different patterns of prehensile hand function. Napier (1956) identified two fundamental prehensile patterns: power grip and precision grip. Power grip is a forceful act executed with the fingers flexed at the MCP, proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints so that the object is held between the surface of the fingers and the palm, with the thumb acting as a buttressing and reinforcing agent (Napier, 1993). The wrist is positioned with ulnar deviation, neutral between flexion and extension. There is an element of precision in power grip; the thumb provides directional control depending on thumb placement. There is some precision when the thumb is adducted, able to contact the object, and gather sensory information and no precision (and maximum power) when the thumb is abducted.

Three patterns of power grip have been identified by Long *et al*. (1970): cylindrical grip, spherical grip, and hook grip (Figure 2.1). Cylindrical grip uses the

extrinsic finger flexors to enable the fingers to surround and maintain grasp on an object. The thumb usually comes around the object and then flexes and adducts to reinforce the clamping action of the fingers. Spherical grip is similar in most aspects to cylindrical grip. The primary difference is that there is a greater spread of the fingers to surround the object. Hook grip is performed primarily by the fingers and may include the palm; the thumb is not included at all. The MCP joints are straight and the PIP and DIP joints are flexed so that the pads of the fingers lie parallel and slightly away from the palm, together forming a hook. Lateral prehension, also known as scissor grip, is another variety of power grip. The object is grasped between the sides of the distal phalanges of the adjacent index and middle fingers. This type of grip is used to statically hold an object that is then transported by movements of the upper extremity.

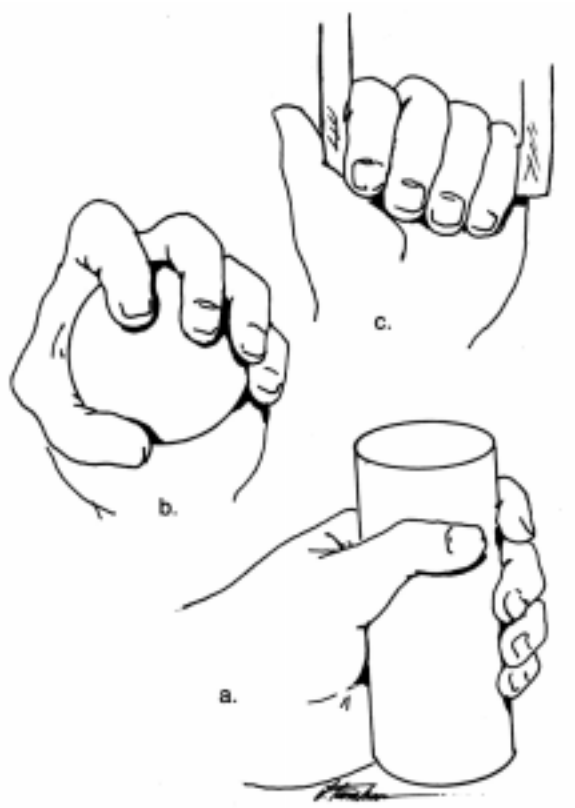


FIGURE 2.1. Three varieties of power grip: (a) cylindrical, (b) spherical, and (c) hook. (From Levangie and Norkin, 2001)

Precision grip involves the manipulation of objects between the thumb and either the distal tip, pad, or side of a finger(s) in a finely controlled manner (Napier, 1993). The fingers are flexed and the thumb is abducted and medially rotated at the MCP and CMC joints. The position of the wrist varies in order to increase the manipulative range of motion. Large objects held in this way involve all the digits, but smaller objects require only the thumb and index finger (two-jaw chuck) or the thumb, index, and middle fingers (three-jaw chuck) (MacKenzie and Iberall, 1994; Levangie and Norkin, 2001). A precision grip is employed when delicacy and accuracy of handling are essential and power is a secondary consideration.

There are three patterns of precision grip that utilize the two-jaw chuck mode of prehension: tip-to-tip prehension, pad-to-pad prehension, and pad-to-side prehension (Figure 2.2). Tip-to-tip prehension involves opposition of the tip of the thumb to the tip of the finger. It is the most precise form of grasp, but also the most easily perturbed (Levangie and Norkin, 2001). Pad-to-pad prehension involves opposition of the pad of the thumb to the pad of the finger. Eighty percent of precision handling uses this form of grasp (Harty, 1971). Pad-to-side prehension, also known as key grip, involves opposition of the pad of the thumb to the side of the index finger. This type of grip is the least precise form of precision handling (Levangie and Norkin, 2001).

A pattern of precision grip that utilizes the three-jaw chuck mode of prehension is the dynamic tripod (Kamakura *et al*., 1980; Wynn-Parry, 1981). An object is held by the pads of the thumb, index, and middle fingers, with an additional contact at the base of the thumb or index finger. These digits have a dynamic function, while the ring and little fingers are used largely for support and static control.

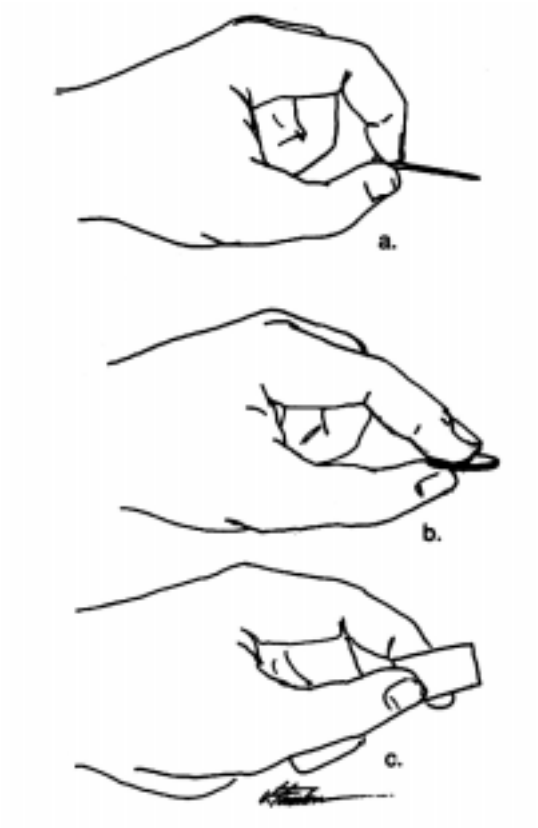


FIGURE 2.2. Three varieties of precision grip: (a) tip-to-tip prehension, (b) pad-to-pad prehension, and (c) pad-to-side prehension. (From Levangie and Norkin, 2001)

2.2. ANATOMY OF THE HAND

The human hand is a complex structure that serves very sophisticated functions. The anatomy of the hand provides a foundation for its extraordinary functional capacity and adaptability. This section will review the skeletal structure of the hand, its nerve and blood supply, and its musculature.

2.2.1. HAND ARTICULATIONS

The hand consists of five digits, four fingers and a thumb (Figure 2.3). The digits are numbered from the radial to the ulnar side: I (thumb), II (index finger), III (middle finger), IV (ring finger), and V (little finger). There are 19 bones and 14 joints distal to

the carpals that make up the hand complex. The entire chain of each finger ray is composed of one metacarpal and three phalanges (two in the thumb). Each finger articulates proximally with a particular carpal bone at the CMC joint. The second to fifth CMC joints have very limited ranges of motion, whereas the first CMC joint of the thumb allows for flexion, extension, abduction, adduction, and opposition. The next joint of each finger links the metacarpal bone to the proximal phalanx at the MCP joint. The MCP joints permit flexion, extension, abduction, and adduction movements. A PIP and DIP joint are found between the phalanges of the fingers; the thumb has only one IP joint. The IP joints permit flexion and extension. The thenar eminence, which is formed by the intrinsic muscles of the thumb, is located at the side of the first metacarpal. The hypothenar eminence, which is created by the muscles of the little finger and an overlying fat pad, is located at the side of the fifth metacarpal.

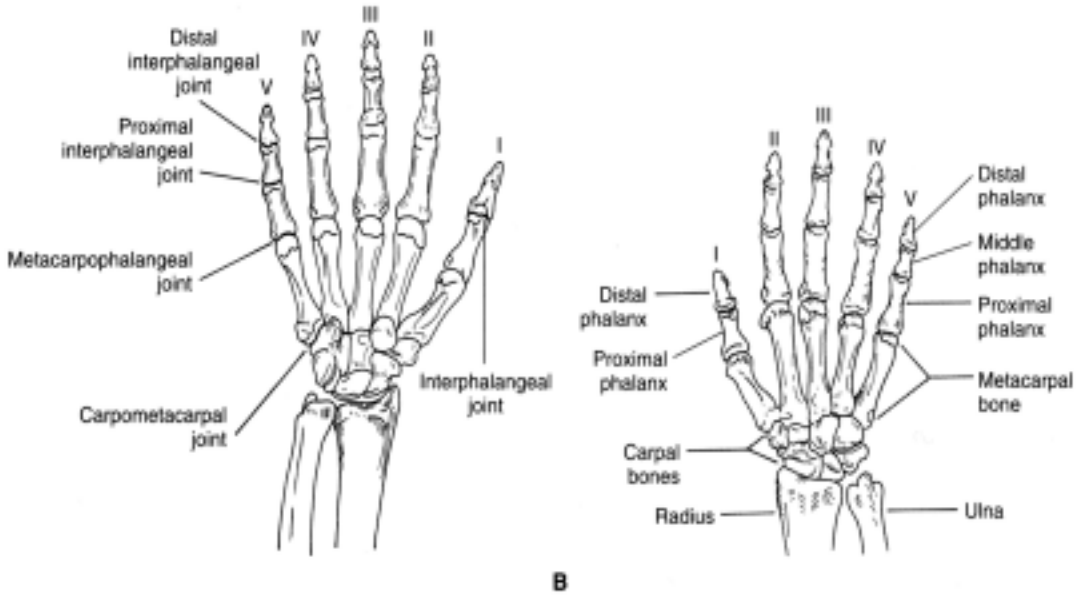


FIGURE 2.3. Schematic drawings of the skeleton of the hand. The finger rays are numbered from the medial to the lateral side. (a) Anterior (palmar) view of the righthand. The joints are labeled. (b) Posterior (dorsal) view of the right hand. The bones are labeled. (From Barr and Bear-Lehman, 2001)

2.2.2. ARCHES OF THE HAND

The bones of the hand are arranged in three arches (Figure 2.4): two transverse arches and one longitudinal arch (Flatt, 1974; Tubiana, 1984). The proximal transverse arch is formed by the trapezoid, trapezium, capitate, and hamate and is relatively fixed. This arch is created not only by the curved shape of the carpals, but also by the transverse carpal and intercarpal ligaments that maintain the concavity of the arch. The distal transverse arch is more mobile and is formed at the level of the metacarpal heads. The transverse metacarpal ligament contributes to the stability of the distal transverse arch during grip functions. The two transverse arches are connected by the longitudinal arch, which is made up of the four digital rays and the proximal carpus. The stability of the MCP joints is essential to the support of the longitudinal arch (Tubiana, 1981). The extrinsic finger flexor and extensor muscles are primarily responsible for changing the shape of the working hand, while the intrinsic muscles of the hand are mainly responsible for maintaining the configuration of the three arches.

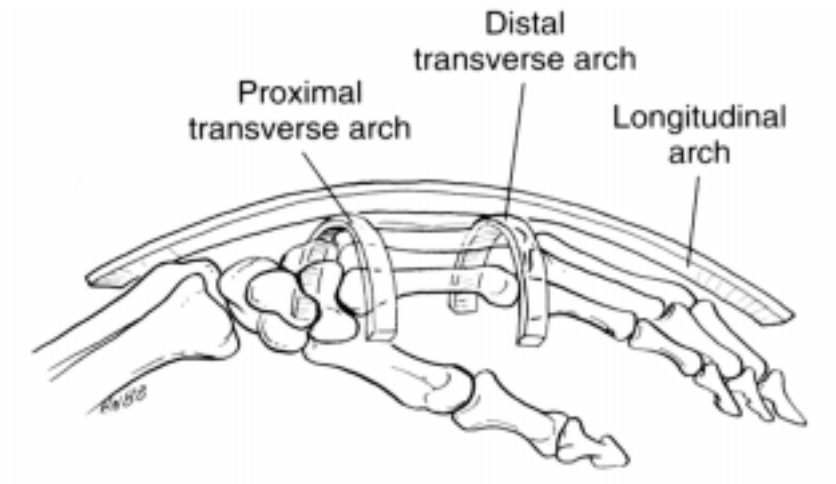


FIGURE 2.4. The three skeletal arches of the hand (mediolateral view). The relatively fixed proximal transverse arch passes through the distal carpus, while the more mobile distal transverse arch passes through the metacarpal heads. The longitudinal arch is composed of the four finger rays and the proximal carpus. (From Barr and Bear-Lehman, 2001)

2.2.3. Nerve and Blood Supply of the Hand

The hand is innervated for sensorimotor function by three peripheral nerves that descend from the brachial plexus: the radial, median, and ulnar nerves. The radial nerve supplies innervation to the extrinsic finger flexor muscle groups in the forearm. Sensory impairment of this nerve minimally impedes hand function. The median nerve innervates the flexor muscle groups in the forearm. In addition, it innervates the thenar muscles and the two radial lumbricals within the hand. The median nerve is most critical to fine motor hand function (Barr and Bear-Lehman, 2001). Impairment of the median nerve affects the flexor muscles on the radial side of the hand more greatly than it does those on the ulnar side. The ulnar nerve shares in the innervation of the flexor digitorum profundus (FDP) and the flexor carpi ulnaris (FCU). Within the hand this nerve supplies the interossei, the adductor pollicis, the third and fourth lumbricals, and the muscles of the hypothenar eminence. Because of the muscles it innervates, the median nerve is regarded as the power source for grip (Barr and Bear-Lehman, 2001).

The principal arterial vessels supplying blood to the hand are the radial and ulnar arteries. The axillary artery passes into the arm to become the brachial artery. This artery descends to the elbow and divides into its two terminal branches, the radial and ulnar arteries. The radial artery passes through the anatomical snuff box and then takes a palmar course where it gives off two large branches to the thumb and index fingers. It then continues on to form the deep palmar arch in conjunction with the ulnar artery. The ulnar artery passes superficial to the flexor retinaculum, gives off a deep branch that completes the deep palmar arch, and continues as the superficial palmar arch and gives off three common digital arteries and a branch to the ulnar side of the little finger.

2.2.4. FINGER MUSCULATURE

Control of the hand is achieved through coordinated action of both the extrinsic and intrinsic musculature (Figures 2.5-2.7). The nine extrinsic muscles, originating from the arm and forearm, are responsible for flexion or extension of the digits. The 19 intrinsic muscles, located entirely within the hand, permit the independent action of each phalanx. Although the contributions of the extrinsic and intrinsic musculature are different, their coordinated activity creates both mobility and stability in a wide range of tasks. The muscles of the hand are summarized in Table 2.1. There are no muscles intrinsic to the carpus; bony structures and ligamentous and tendinous tissues play major roles in controlling finger movements. In this sense, the carpus acts as a bridge for muscle action and force transmission between the hand and forearm.

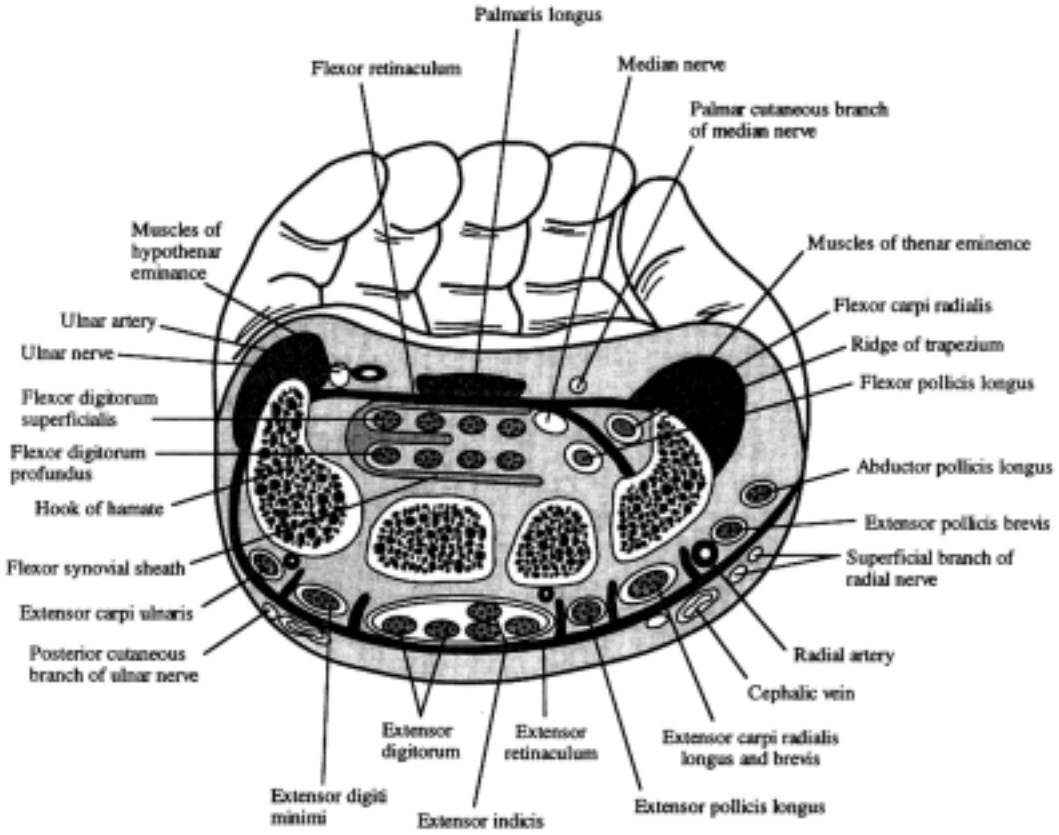


FIGURE 2.5. Transverse section of the hand at the carpal level. (From Page, 1998)

TABLE 2.1. Muscles of the hand and their actions.

Muscle	Action
Extrinsic Muscles	
Flexors	
Flexor digitorum superficialis	Flexion of PIP and MCP joints
Flexor digitorum profundus	Flexion of DIP, PIP, and MCP joints
Flexor pollicis longus	Flexion of IP and MCP joints of thumb
Extensors	
Extensor pollicis longus	Extension of IP and MCP joints; secondary adduction of the thumb
Extensor pollicis brevis	Extension of MCP joint of thumb
Abductor pollicis longus	Abduction of thumb
Extensor indicis proprius	Extension of index finger
Extensor digitorum communis	Extension of fingers
Extensor digiti minimi	Extension of little finger
Intrinsic Muscles	
Interossei (all)	Flexion of MCP joints and extension of PIP and DIP joints
Dorsal interossei	Spread of index finger away from long finger
Palmar interossei	Adduction of index, ring, and little fingers toward long finger
Lumbricals	With extensor, extension of PIP and DIP joints
Thenar muscles	
Abductor pollicis brevis	Abduction of thumb
Flexor pollicis brevis	Flexion and rotation of thumb
Opponens pollicis	Rotation of first metacarpal toward palm
Hypothenar muscles	
Abductor digiti quinti	Abduction of little finger (flexion of proximal phalanx, extension of PIP and DIP joints)
Flexor digiti quinti brevis	Flexion of proximal phalanx of little finger and forward rotation of fifth metacarpal
Adductor pollicis	Adduction of thumb

(Adapted from Barr and Bear-Lehman, 2001)

2.2.4.1. Extrinsic Finger Flexors

There are two muscles that originate outside the hand that contribute to finger flexion: the flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP) (Figure 2.6). The FDS can flex the MCP joint and the PIP joint. The FDP can flex the MCP, PIP, and DIP joints and is considered to be the more active of the two muscles (Levangie and Norkin, 2001). When performing gentle pinching or grasping actions, the FDP alone will be active. The FDS is responsible for finger flexion only when flexion of the DIP joint is not required. When simultaneous PIP and DIP flexion are required, the

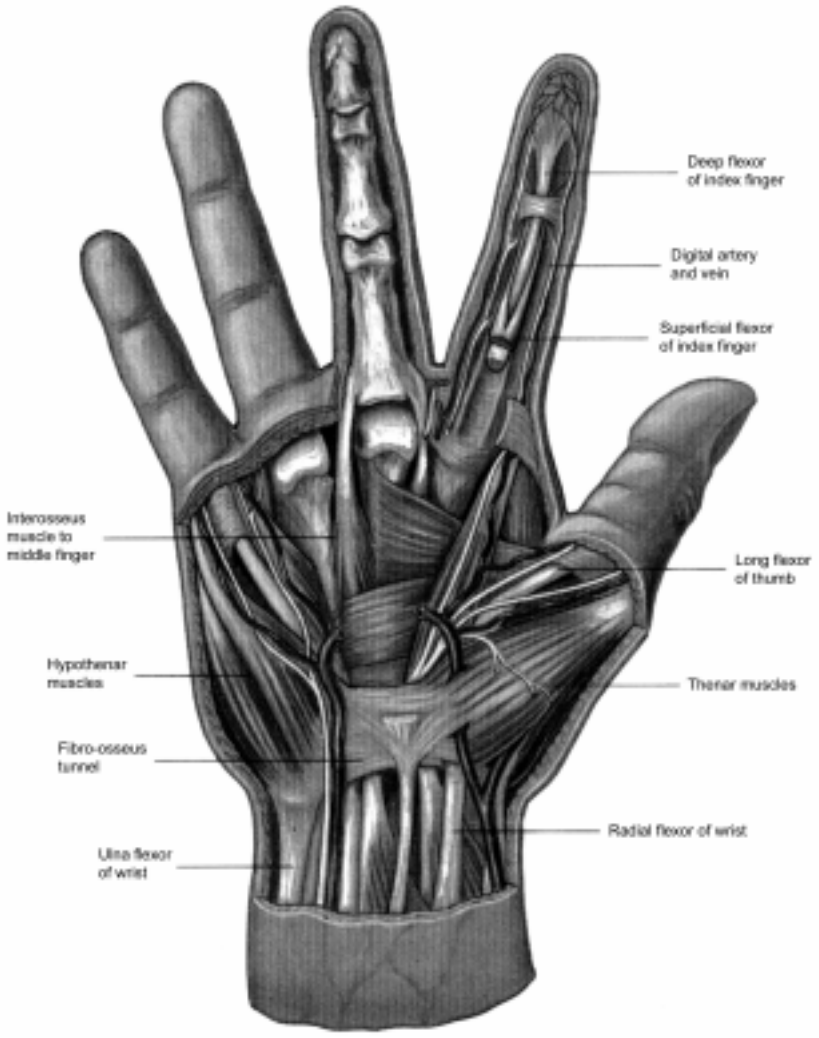


FIGURE 2.6. Palmar view of a dissection of a hand. (From Napier, 1993)

FDS acts as a reserve muscle. It works in conjunction with the FDP by increasing its activity as increased flexor force is needed in power grip and contributes to finger flexion when the wrist is flexed (Boivin *et al*., 1969; Brook *et al*., 1995; Long *et al*., 1970; Valentin, 1981a).

2.2.4.2. Extrinsic Finger Extensors

The extrinsic finger extensors are the extensor digitorum communis (EDC), the extensor indicis proprius (EIP), and the extensor digiti minimi (EDM) (Figure 2.7). The EIP and EDM insert into EDC structure of the index and little finger, respectively, at the extensor hood. These muscles appear to add independence of action to the index and ring fingers rather than additional strength (Levangie and Norkin, 2001). The EDC tendons of one finger may also be connected to the tendon(s) of an adjacent finger by junctura tendinae. These interconnections result in active extension of one finger being accompanied by passive extension of the adjacent finger(s); the patterns of interdependence vary with the intertendinous connections. The connections between the EDC, EIP, and EDM, and junctura tendinae generally result in the index finger being the most independent digit in extension, followed by the little, middle, and ring fingers in decreasing order of independence (Ranney, 1995).

The EDC, EIP, and EDM are the only muscles capable of extending the MCP joints of the fingers. Even though these muscles have no direct attachments to the proximal phalanx, active tension on the extensor hood from one or more of these muscles will result in extension of the MCP joint. The extrinsic muscles alone cannot produce extension at either the PIP or DIP joints. Active PIP and DIP extension requires contributions from two intrinsic muscle groups, the interossei and lumbricals.

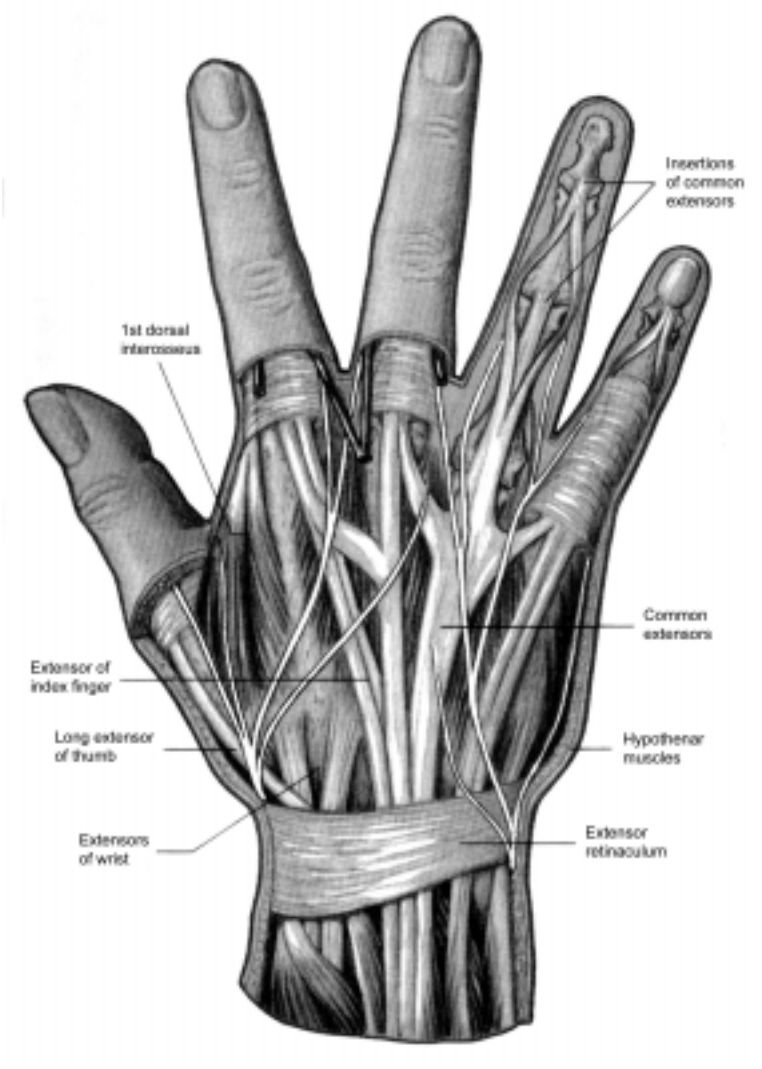


FIGURE 2.7. Dorsal view of a dissection of a hand. (From Napier, 1993)

2.2.4.3. Intrinsic Finger Musculature

The dorsal interossei (DI) and palmar interossei (PI) are groups of muscles arising from between the metacarpals and attaching to the bases of the proximal phalanges or to the extensor assembly. There are four DI muscles (one to each finger) and three or four PI muscles (the PI of the thumb is not described by all anatomists). The interossei flex the MCP joint and extend the PIP and DIP joints. The interossei also stabilize the MCP joint during extension. In addition, when the MCP joint is extended, the DI and PI are

effective abductors and adductors, respectively, of the MCP joint. Finally, the interossei produce some rotation of the MCP joint, which is extremely important in prehension (Valentin, 1981b).

The lumbricals are four small muscles that interconnect the deep flexors to the extensor apparatus of the fingers. The lumbricals are the only muscles in the human body that have no direct bony attachments; they attach at both ends to tendons of other muscles. The lumbricals are strong extensors of the PIP and DIP joints and relatively weak MCP joint flexors regardless of MCP joint position (Levangie and Norkin, 2001; Valentin, 1981b). In addition, the lumbricals play a part in side-to-side and rotation movements of the fingers.

Due to the interaction of the extrinsic and intrinsic finger flexor and extensor musculature, the actions of the PIP and DIP joints are functionally coupled. The coupled actions of the PIP and DIP joints can be summarized as follows (Levangie and Norkin, 2001): (1) active extension of the PIP joint will be accompanied by extension of the DIP joint, (2) active or passive flexion of the DIP joint will be accompanied by PIP flexion, and (3) full active or passive flexion of the PIP joint will prevent active extension of the DIP joint.

2.2.4.4. Extrinsic Thumb Muscles

There are four extrinsic thumb muscles: the flexor pollicis longus (FPL), the extensor pollicis brevis (EPB), the abductor pollicis longus (APL), and the extensor pollicis longus (EPL). The FPL inserts on the distal phalanx and is the correlate of the FDS: it can flex the MCP joint and the IP joint. It is the only muscle capable of flexing the distal phalanx of the thumb. The short extensor (EPB) and the long abductor (APL)

abduct the CMC joint. The EPB also extends the MCP joint. The EPL inserts on the distal phalanx. The intrinsic thumb muscles that attach to the EPL tendon can extend the IP joint, but only to the neutral position. The EPL can complete the full range of extension at the IP joint, as well as causing extension at the MCP joint. The EPL also extends and adducts the CMC joint of the thumb. Unlike the fingers, each joint of the thumb has a separate extensor tendon. The APL, EPB, and EPL are attached to the bases of the metacarpal, proximal phalanx, and distal phalanx, respectively.

2.2.4.5. Intrinsic Thumb Muscles

There are five intrinsic thumb muscles that originate from the carpal bones and the flexor retinaculum. The opponens pollicis (OP) is the only intrinsic thumb muscle to attach to the first metacarpal. The OP serves to abduct, flex, and rotate the metacarpal. The abductor pollicis brevis (APB), flexor pollicis brevis (FPB), adductor pollicis (ADP), and first PI all insert on the proximal phalanx. The FPB causes flexion of the MCP joint. The APB, along with the lateral head of the FPB, abductor force to the MCP joint. The ADP, along with the medial head of the FPB, can adduct the thumb at the MCP joint. The first PI assists with flexion and adduction of the MCP joint. Although generally not regarded as an intrinsic thumb muscle, the first DI may also contribute to thumb function by assisting with thumb adduction.

The intrinsic muscles of the thumb are active during most grasping activities, regardless of the position of the thumb. Most frequently, the OP works in conjunction with the APB and FPB, although the relative muscle activity varies with the posture of the thumb (Levangie and Norkin, 2001). In addition, the ADP serves to stabilize the thumb against a finger or an object during opposition.

2.3. BIOMECHANICS OF THE HAND

This section will review the biomechanics of the human hand (for reviews, see Barr and Bear-Lehman, 2001; Brand and Hollister, 1999; Chao *et al*., 1989; Hajian and Howe, 2000; Schuind *et al*., 1994). Because hands perform such an important role in our mechanical interactions with the environment, a description of the kinematics and kinetics of the human hand is essential to fully understand prehension.

2.3.1. KINEMATICS

The hand is extremely mobile and can perform an infinite variety of movements. The kinematic properties of the digits allow the hand to mold itself to objects of different shapes and sizes during grasping and allow for its tremendous versatility.

2.3.1.1. Range of Motion

The different shapes of the CMC, MCP, and IP joints of the fingers and thumb result in varying degrees of freedom (DOF) at each of these joints (Craig, 1992). In addition, the orientation of the thumb and the unique configuration of its CMC joint provide this digit with a large range of motion and great flexibility (Hollister and Giurintano, 1995; Imaeda *et al*., 1992). The resting posture of the hand is in a position of equilibrium without active muscle contractions: the wrist is extended 20° and in neutral radial/ulnar deviation, the MCP joints are flexed approximately 45°, the PIP joints are flexed between 30-45°, and the DIP joints are flexed between 10-20° (Napier, 1993).

The second and third metacarpals are connected to each other and to the trapezoid and capitate by joints that are basically immobile and permit little motion (Pagowski and Piekarski, 1977). The fourth CMC joint is a plane joint with one DOF that allows

approximately 10-15° flexion/extension (Barr and Bear-Lehman, 2001). The fifth CMC joint is a saddle joint with two DOFs that permits approximately 20-30° of flexion/extension and some abduction/adduction (Barr and Bear-Lehman, 2001). Limited palmar displacement of the fourth and fifth metacarpals allows for cupping of the hand to occur, which is essential for grasping (Levangie and Norkin, 2001).

The MCP joints of the fingers are condyloid joints with two DOFs that permit flexion/extension and abduction/adduction (Youm *et al*., 1978). Flexion of the MCP joints is approximately 90°, with the little finger demonstrating the most flexion (about 95°) and the index finger the least flexion (about 70°) (Barr and Bear-Lehman, 2001; Levangie and Norkin, 2001). Extension beyond the zero position varies widely among individuals and depends on joint laxity.

The PIP and DIP joints of the digits are hinge joints with one DOF that allows flexion/extension (Landsmeer, 1975). Flexion of approximately 110° and 90° occurs in the PIP and DIP joints, respectively (Barr and Bear-Lehman, 2001; Levangie and Norkin, 2001). Extension beyond the zero position is regularly observed in these joints and depends largely on ligamentous laxity.

The CMC joint of the thumb is a saddle joint with two DOFs that permits flexion/extension and abduction/adduction (Hollister and Giurintano, 1995; Imaeda *et al*., 1992). The thumb metacarpal moves through a conical range of motion extending from the plane of the hand in a palmar direction. The most important motion of the thumb is opposition, in which abduction and rotation at the CMC joint moves the thumb toward the little finger; MCP and IP joint flexion places the thumb in close proximity to the fingertips. Flexion of the MCP joint ranges from 30-90°, while the IP joint has a range of

motion similar to that observed in the DIP joints of the fingers (Barr and Bear-Lehman, 2001; Levangie and Norkin, 2001).

Active ranges of motion of the joints of the fingers and thumb are well documented, but there is little data reporting the functional ranges of motion required to perform activities of daily living. In the fingers, only a small percentage of the active range of motion of the joints was required for functional tasks (Hume *et al*., 1990). During 11 activities of daily living, functional flexion averaged 61° at the MCP joint, 60° at the PIP joint, and 39° at the DIP joint. In the thumb, functional flexion averaged 21° at the MCP joint and 18° at the IP joint. The joint flexion angles for the index finger in a variety of static tasks are presented in Table 2.2. These hand functions include basic pinch and grasp, flexion/extension, radial/ulnar deviation, abduction/adduction with the middle finger, and several common activities of daily living.

TABLE 2.2. Joint flexion angles for various functions.

Hand Function	DIP Joint	PIP Joint	MCP Joint
Tip pinch	25°	50°	48°
Key pinch	20°	35°	20°
Pulp pinch	0°	50°	48°
Grasp	23°	48°	62°
Abduction	0°	0°	0°
Adduction	0°	0°	0°
Flexion	0°	0°	0°
Extension	0°	0°	45°
Briefcase grip	55°	72°	23°
Holding glass	20°	48°	5°
Opening big jar	35°	55°	50°

(Data from Chao *et al*., 1989)

2.3.1.2. Tendon Excursions

As a digit moves through its range of motion, each tendon slides a certain distance (An *et al*., 1983; Storace and Wolf, 1982). Excursion takes place simultaneously in the flexor and extensor tendons during joint motion: the tendons of the agonist muscles displace in one direction, while the tendons of the antagonist muscles displace in the opposite direction. Knowledge of tendon excursions has applications for the theoretical calculations of muscle forces, rehabilitation of the hand after tendon repair, and surgical procedures such as tendon transfers (Brand and Hollister, 1999; Chao *et al*., 1989).

The relationship between the excursions of the finger tendons and the angular displacement of the MCP, PIP, and DIP joints has been reported to be both linear (Elliot and McGrouther, 1986) and nonlinear (Armstrong and Chaffin, 1978). The values for tendon excursions are presented in Table 2.3. In the digital tendons, the excursions are larger in the more proximal joints. In addition, the excursion of the flexor tendons is larger than that of the extensor tendons, and the excursion of the extrinsic muscle tendons is larger than that of the intrinsic tendons.

TABLE 2.3. Approximate total excursions of finger muscle tendons.

Muscle	Tendon Excursion (mm)
Interossei	30
Extensor pollicis brevis	30
Abductor pollicis longus	30
Lumbricals	40
Thenar muscles	40
Finger extensors	50-60
Finger flexors	60-70

(Data from An *et al*., 1983)

2.3.1.3. Patterns of Finger Coordination

The importance of coordinated finger motion is evident in many activities of daily living. The path taken by the fingertips of the human hand during unrestricted flexion and extension follows a precise mathematical pattern: an equiangular spiral (Gupta *et al*., 1998; Littler, 1973). This spiral is a series of isosceles triangles, each with an apical angle of 36°. The equiangular curve created by the fingertips as they close is determined by the ratios of the average segment lengths of the metacarpals (7.1 cm), proximal phalanges (4.6 cm), middle phalanges (2.8 cm), and distal phalanges (1.8 cm). This curve allows for the hand's adaptability in grasping objects of different shapes and sizes (Barr and Bear-Lehman, 2001; Levangie and Norkin, 2001).

Flexion and extension of the interphalangeal joints follow well-defined patterns of movement. These patterns result from biomechanical extensor and flexor constraints in the fingers (Buchner *et al*., 1988). During grasping, it has been demonstrated that the motion of the PIP joint begins before the DIP joint motion in finger flexion movements (Holguin *et al*., 1999; Nakamura *et al*., 1998; Tubiana, 1981). Conversely, during finger extension, the motion of the DIP joints begins before the motion of the PIP joint (Holguin *et al*., 1999; Nakamura *et al*., 1998; Tubiana, 1981). However, it should be noted that Darling *et al*. (1994) observed nearly linear relationships for angular position between the PIP and DIP joints, and between the MCP and PIP joints during index finger movements that were varied in speed and direction. They concluded that the highly coordinated action of the extrinsic finger muscles during flexion and extension are important contributors to the linked motions of the PIP and DIP joints because these muscles span two or all three of the index finger joints.

2.3.1.4. Interaction of Wrist and Hand Motion

Wrist motion plays an important role in assisting the control of the fingers and hand during grasping. As the wrist changes its position and the lengths of the finger flexor tendons are altered, the resultant grip forces in the fingers vary (Hazelton *et al*., 1975; Lamoreaux and Hoffer, 1995; O'Driscoll *et al*., 1992; Pryce, 1980; Volz *et al*., 1980). Hazelton *et al*. (1975) studied the influence of wrist position on the force produced at the middle and distal phalanges and found that the greatest force was generated with the wrist in ulnar deviation, followed by extension, and the least in flexion. Volz and colleagues (1980) analyzed grip strength in five wrist positions: 40° and 20° of flexion, neutral, and 20° and 40° of extension. They discovered that grip strength was greatest at approximately 20° of wrist extension and least at 40° of wrist flexion. O'Driscoll *et al*. (1992) reported that maximum grip strength occurred at approximately 35° wrist extension, with reductions in grip strength up to 73% when the wrist position deviates from the optimum position. Taken together, the results of these studies indicate that to generate maximal grip force, the wrist must be stable and in slight extension and ulnar deviation.

2.3.2. KINETICS

The following section will present a discussion of the muscle forces acting on the fingers and thumb during basic prehensile functions of the hand, the internal forces on the joints of the hand during various isometric hand functions, and the contributions and coordination of individual fingers (i.e., force synergies) in multiple finger prehension. In addition, the biomechanics and control of force and torque production in static multi-finger prehension will be reviewed.

2.3.2.1. Muscle Forces in the Hand

Biomechanical models have been used to estimate the muscle forces in the hand during a variety of activities (Brook *et al*., 1995; Chao *et al*., 1989; Dennerlein, 2000; Giurintano *et al*., 1995; Harding *et al*., 1993; Li *et al*., 2000, 2001; Sancho-Bru *et al*., 2001; Smith *et al*., 1964; Weightman and Amis, 1982). The values most often cited for the strengths of the extrinsic muscles of the hand are presented in Table 2.4. Note that the units of strength are presented in terms of work (Nm), i.e., the force of a muscle multiplied by its tendon excursion. The values presented by von Lanz and Wachsmuth (1970) show that the strength of the finger flexors is over twice that of the extensors. The ratios of FDP and FDS tendon-to-tip forces during isometric pinch range from 1.5 to 6.0 (Chao *et al*., 1989; Dennerlein, 2000); the ratio depends on the DIP joint posture. Also, it has been reported that the intrinsic muscles generate forces that are roughly 80% of those produced by the extrinsic finger flexors (Ketchum *et al*., 1978).

TABLE 2.4. Static strength values of the extrinsic muscles of the hand.

Muscle	Strength (Nm)
Flexor pollicis longus	12
Extensor pollicis longus	1
Abductor pollicis longus	
As a wrist flexor	1
As a wrist abductor	4
Extensor pollicis brevis	1
Flexor digitorum superficialis	48
Flexor digitorum profundus communis	45
Extensor digitorum communis	17
Extensor indicis proprius	5

(Data from von Lanz and Wachsmuth, 1970)

2.3.2.2. Forces in the Hand During Pinch and Grip

Forces produced during prehension have been measured during various hand functions, namely power grip and different types of thumb-index pinch (Amis, 1987; Dickson *et al*., 1972; Ejeskär and Örtengren, 1981; Kinoshita *et al*., 1995, 1996a,b; Lee and Rim, 1991; Li *et al*., 1998b; Radhakrishnan and Nagaravindra, 1993; Radwin *et al*., 1992; Swanson *et al*., 1970). The results from these studies demonstrate that grasping forces are precisely controlled, and vary with the weight and size of the object being held and the frictional conditions during grasping. The average values for the strength of the index finger during grip and various thumb-index pinch positions are listed in Table 2.5.

TABLE 2.5. Average strength of the index finger during isometric hand functions.

Hand Function*	Strength (N)
Tip pinch	24-95
Key pinch	37-106
Pulp pinch	30-83
Grasp	
Distal phalanx	38-109
Middle phalanx	7-38
Proximal phalanx	23-73

*For tip and pulp pinch, the forces were applied on the tip and pulp of the distal phalanx, respectively. For key pinch, these forces were applied on the radial side of the middle phalanx. For grasp functions, forces were applied at the middle of each phalanx.
(Data from An *et al*., 1985)

The maximum flexion forces produced by individual fingers vary from 50-60 N for the index and middle fingers to 25-35 N for the ring and small fingers (Radwin *et al*., 1992). Ejeskar and Ortengren (1981) reported that the middle finger is the strongest

digit, followed by the index, ring, and little fingers. The maximum force that an individual finger can produce decreases in proportion to the number of other fingers participating in a task, which suggests that there is inhibition of the hand muscles when they are simultaneously active (Li *et al*., 1998a,b; Ohtsuki, 1981; Radwin *et al*., 1992).

Studies examining force control of finger movements have primarily involved maximal voluntary force production, so data regarding the magnitude of submaximal forces generated during repetitive movements such as those made when typing are sparse. The activation forces for most keyboards are typically less than 1 N (August and Weiss, 1992). However, for skilled typists the peak keystroke forces are much higher than this and range between 1.8 (little finger)-3.3 N (thumb); this is approximately five times greater than the key switch make force (Armstrong *et al*., 1994; Martin *et al*., 1996). The mean keystroke force is considerably lower, ranging between 0.8-0.9 N for skilled typists, and this force does not vary significantly across fingers (Martin *et al*., 1996).

Numerous investigators have created analytical models to examine the internal forces in the joints of the fingers and thumb during hand function (Berme, 1980; Chao *et al*., 1976, 1989; Fowler and Nicol, 1999, 2000; Harding *et al*., 1993; Purves and Berme, 1980; Weightman and Amis, 1982). The compressive forces in the MCP, PIP, and DIP joints for various hand functions are shown in Table 2.6. These forces were smallest in the DIP joint and became larger in the PIP and MCP joints. The greatest forces were produced during lateral key pinch, followed by opening a big jar. Cooney and Chao (1977) studied the internal forces in the thumb and showed that during pinch with an applied force of 10 N the joint compression force ranged from 60-134 N at the CMC joint, 46-66 N at the MCP joint, and 24-36 N at the IP joint.

TABLE 2.6. Joint compressive force (in units of applied force, N) at the DIP, PIP, and MCP joints of the index finger during isometric hand functions.

Hand Function	DIP Joint	PIP Joint	MCP Joint
Tip pinch	2.4-2.7	4.4-4.9	3.5-3.9
Key pinch	2.9-12.5	4.9-19.4	14.7-27.1
Pulp pinch	3.0-4.6	4.8-5.8	4.0-4.6
Grasp	2.8-3.4	4.5-5.3	3.2-3.7
Briefcase grip	0.0-0.0	1.7-1.9	1.0-1.3
Holding glass	2.5-2.9	4.3-4.4	4.0-4.1
Opening big jar	5.2-9.5	7.2-14.2	14.8-24.3

(Data from An *et al*., 1985)

2.3.2.3. Force Control in Multi-Finger Prehension

Biomechanical constraints create limitations on the planning and control of prehension. For example, if a functional constraint during grasping is to ‘not drop the object’, the posture of the hand and individual finger forces must be chosen to ensure a stable grasp. The three requirements for a stable grasp are (MacKenzie and Iberall, 1994): (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 magnitude of the grasping force to prevent any displacement due to an arbitrary applied force.

Because the set of five digits is redundant for the control of a hand-held object, the grip force can be distributed among the involved fingers in many different ways. Numerous studies have examined the distribution of grasp forces between the four digits opposing the thumb (Ohtsuki 1981, Amis 1987, Kinoshita *et al*. 1995, Radwin *et al*.

1992, Li *et al*. 1998a). The following three phenomena have been observed during precision gripping and pressing tasks: (a) *force sharing* – the total force produced by all the involved fingers is shared among the fingers in a specific manner (Amis 1987, Radwin *et al*. 1992, Kinoshita *et al*. 1995, Li *et al*. 1998a, b); (b) *force deficit* – the force produced by a given finger in a multi-finger task is smaller than the force generated by this finger in a single-finger task (Ohtsuki 1981, Kinoshita *et al*. 1996, Li *et al*. 1998a, b, 2001); and (c) *enslaving* – the fingers that are not required to produce any force by instruction are involuntarily activated (Latash *et al*. 1998, Li *et al*. 1998a, b; Zatsiorsky *et al*., 1998, 2000). Enslaving effects reveal the existing biomechanical and neurophysiological interconnections among the fingers: a neural command to one finger induces activation of other fingers (cf. Schieber, 1991, 1996; Häger-Ross and Schieber, 2000).

Force sharing among fingers has mainly been addressed during studies examining handgrip or pinch (Amis, 1987; Hazelton *et al*., 1975; Kinoshita *et al*., 1995, 1996a, b; Li *et al*., 1998a; Radhakrishnan and Nagaravindra, 1993; Radwin *et al*., 1992; Rielmann *et al*., 2001; Talsania and Kozin, 1998; although see Li *et al*., 1998b; Ohtsuki, 1981). There are large differences of reported force sharing patterns during multi-finger force production tasks (Table 2.7). These differences may arise due to two possible factors: the requirement of the task (e.g., grasp vs. press) and the position of the thumb during grasping. Different tasks may require different force sharing patterns. According to basic mechanics, static grip and pinch tasks require that the force produced by the thumb is equal and opposite in magnitude to the total force generated by the opposing fingers. Therefore, the maximal total force produced is limited by the force of the thumb and may

TABLE 2.7. Finger force sharing values during various hand functions.

Author(s), year	Task	I	M	R	L
Amis, 1987	Grasp, MVC	30.0	30.0	22.0	18.0
Hazelton et al., 1975	Grasp, MVC	25	33.5	25	16.5
Kinoshita et al., 1995	Grasp, MVC	42.0	27.4	17.6	12.9
Li et al., 1998a	Press, MVC	31.0	33.1	23.0	12.9
Li et al., 1998b	Grasp, MVC	38.0	23.5	20.1	18.4
Ohtsuki, 1981	Pull, MVC	24-25	33	27-28	15
Radhakrishnan and Nagaravindra, 1993	Grasp, MVC	31	33	22	14
Radwin et al., 1992	Pinch at 10%, 20%, 30% MVC	33.1	32.5	17.2	15.3
	Grasp to lift load of 1.0, 1.5, 2.0 kg	34.7	26.4	20.1	18.8
Talsania and Kozin, 1998	Grasp, MVC	25	35	26	15

MVC = maximal voluntary contraction

not represent the true maximum force of the fingers. Also, in order to prevent the rotation of an object during grasping, the individual fingers should produce forces such that the total moment of force with respect to the thumb is equal to zero. Hence, force sharing patterns in gripping tasks may be defined by additional mechanical constraints. Finger pressing tasks are not constrained by the requirement to maintain equilibrium. In addition, force sharing patterns among fingers are strongly dependent upon the thumb location during grasping (Li *et al*., 1998a)

2.3.2.4. Torque Control in Multi-Finger Prehension

When manipulating a hand-held object, one needs to apply sufficient force to prevent the object from slipping out of the hand. In addition, one needs to control the total torque exerted on the object such that it remains vertical or at a controlled angle.

Usually, the requirements for grip force stabilization allow for some laxity, while the requirements for total torque production are highly specified. The grip force needs only to be larger than the slip threshold and smaller than the force that would damage the object or result in injury. In contrast, the torque applied to the object needs to be precisely controlled since any error will lead to unwanted rotation of the object.

During manipulation of an object, the fingers may act as *force agonists* and *torque antagonists*. To prevent the object from slipping, the fingers act as agonists; each of them contributes to the total grip force. In contrast, the index and middle fingers and the ring and little fingers exert moments of force in opposite directions about an axis of rotation created by the thumb. These two pairs of fingers are torque antagonists.

Investigations on torque production during grasping are scarce; previous studies have mainly addressed slip force and slip prevention (Goodwin *et al*., 1998; Jenmalm *et al*., 2000; Johansson *et al*., 1999; Kinoshita *et al*., 1997; Salimi *et al*., 2000). In these experiments, subjects grasped objects with the tips of the index finger and thumb; force sharing was not discussed. It has been demonstrated that the minimum grip force required to stabilize an object subjected to a torque load increases linearly with both torque and tangential force (Kinoshita *et al*., 1997; Johansson *et al*., 1999). In a recent experiment performed by Santello and Soechting (2000) subjects were asked to hold a handle for 30 s. In different trials, the location of the center of mass of the handle was changed; this caused the external torque to vary. The study focused mainly on the continuous oscillations of the individual finger forces during the holding period. It was demonstrated that, in all frequency bands, the oscillations of the different finger forces were synchronous and, hence, determined by a multi-finger synergy.

2.4. CONTROL OF THE HAND

Skilled manual actions involve grasping, transporting, and manipulating objects. Grasping itself entails orienting and shaping the hand and fingers in relation to an object's physical characteristics. Grasp stability requires control of the forces applied to the object, so it is neither damaged nor dropped. In addition, the manipulation of objects requires the independent control of finger movements. In this section, various aspects of the control of precision grip in humans will be discussed (for a review, see Lemon, 1999).

2.4.1. CENTRAL NEURAL MECHANISMS

Little is known about how the CNS implements the specific sensorimotor control functions used by humans in manipulative tasks. It appears that the control of grasping relies on distributed processes in the CNS, utilizing most areas known to be involved in control processes pertaining to limb actions (for a review, see Lawrence, 1994).

2.4.1.1. Primary Motor Cortex

The representation of the hand area in the primary motor cortex (M1) is well established from stimulation experiments (Penfield and Boldrey, 1937; Woolsey *et al*., 1951, 1979) and functional magnetic resonance imaging (fMRI) (Boroojerdi *et al*., 1999; Yousry *et al*., 1995, 1997). The selection of the appropriate muscles to perform a task is the responsibility of M1. Therefore, M1 plays a fundamental role in the execution of prehensile tasks, especially precision grip (Kuhtz-Buschbeck *et al*., 2001; Kuypers, 1981; Lawrence and Kuypers, 1968; Porter and Lemon, 1993). Also, through its influences on the spinal cord, M1 can modulate activity in all of the motoneuron pools involved in reach and grasp (Johansson *et al*., 1994; Lemon *et al*., 1995; Picard and Smith, 1992).

2.4.1.2. Supplementary Motor Area

The supplementary motor area (SMA) is thought to be responsible for the preparation and programming of hand movements, especially for complex tasks (Rao *et al*., 1995; Roland *et al*., 1980; Tanji, 1994). Rao *et al*. (1995) and Roland *et al*. (1980) have used fMRI and regional cerebral blood flow studies, respectively, to document increased SMA activity when using several digits or joints and planning a complex sequence of movements. Evidence also suggests that SMA may be directly involved in controlling movement execution together with M1 (Rouiller, 1996). Another function proposed for SMA is the control of bimanual movements (Wiesendanger *et al*., 1996).

2.4.1.3. The Basal Ganglia

The basal ganglia are of importance for the processing of sensory information used to guide the motor commands of precision grip lifting tasks. The role of the basal ganglia in sensory processing has been studied in individuals with Parkinson's disease (PD) (Ingvarsson *et al*., 1997; Müller and Abbs, 1990). While PD individuals adequately adjust their grip force to compensate for the load forces associated with objects of different weights, they utilize a much higher safety margin than control subjects. This finding could not be explained in terms of force production deficits, but rather by impairments in the use of sensory information to guide motor output.

2.4.1.4. Cerebellum

Studies have shown a relationship between cerebellar Purkinje cell discharge rate and object weight and/or friction both prior to and during grasping (Dugas and Smith, 1992; Espinoza and Smith, 1990). This suggests that the cerebellum plays a role in

anticipatory parameter control pertaining to the physical properties of an object. Müller and Dichgans (1994) and Serrien and Wiesendanger (1999a, b) have examined grip and load force coupling in cerebellar patients. These individuals were able to adapt their grip force levels to different object load forces, but they were less efficient than healthy controls in using sensorimotor memory about object weight and surface friction. This was demonstrated by rates of change in grip force that are characteristic of a lack of sufficient anticipatory parameter control.

2.4.1.5. Sensory and Association Cortex

The primary somatosensory cortex (S1) participates in the regulation of fine grip forces during precision grip, but is not involved in force generation (Chapman *et al*., 1996; Wannier *et al*., 1991). Hikosaka *et al*. (1985) have shown that S1 inactivation results in the loss of the ability to manipulate small objects.

The posterior parietal and premotor cortical areas have been implicated in the control of object-oriented manual actions (Goodale and Milner, 1992; Jeannerod, 1994a, b). These cortical areas accomplish this by maintaining spatiotemporal maps, which permit the integration of proprioceptive, tactile, and visual cues necessary for grasp and manipulation (Jeannerod, 1988; Pause *et al*., 1989). In addition, separate representations may exist within the parietal cortex for pointing, reaching, and grasping movements (Gallese *et al*., 1994; Jeannerod, 1994a).

2.4.2. Control of Prehension During Object Contact

Before describing the sensorimotor control of grasping and manipulation, it is useful to present the terms grip force, load force, slip ratio, and safety margin (for

reviews, see Johansson, 1996; Johansson and Cole, 1992, 1994). The *grip force* is the force normal to the grip surfaces; in a precision grip, the thumb and finger(s) contact surfaces on opposite sides of the object. The *load force* is the resultant of the gravitational and inertial forces acting on an object. When holding an object in a stationary position, the load force is equal to the weight of the object. At a given load force there is a minimum grip force required to prevent slip, the *slip force*. The grip force must be large enough to develop a friction force at the digit-object interface that exceeds the shear force due to the load force. Therefore, to prevent slip the grip force:load force ratio must exceed a certain minimum, termed the *slip ratio*, at which the object starts to slip from grasp (Johansson and Westling, 1984). The grip force that people use when holding an object is generally 10-40% greater than the minimum required to prevent slip. This excess force results in a *safety margin*, which is defined as the ratio of the excess grip force to the minimum grip force that just prevents slipping (Westling and Johansson, 1984; Kinoshita *et al*., 1997).

2.4.2.1. Adaptation to the Surface of the Object

In order to stabilize an object within our grasp as we move the object or use it as a tool, we must apply an adequately large grip force. At the same time, we must not use an excessive grip force that may damage the object or injure the hand. This is not trivial, since we encounter different coefficients of friction for various materials as well as changes in skin friction in everyday situations. For example, the coefficients of static friction with respect to the skin are 1.21, 0.68, and 0.35 for sandpaper, suede, and silk, respectively (Johansson and Westling, 1984). It has been shown that individuals automatically adjust the grip force:load force ratio to these changes in friction; the more

slippery the digit-object interface the higher the grip force:load force ratio (Johansson and Westling, 1984; Westling and Johansson, 1984). By adapting the grip force:load force ratio in this manner, individuals are able to maintain a fairly constant safety margin independent of the frictional condition of the digit-object interface.

2.4.2.2. Adaptation to the Weight of the Object

It has also been demonstrated that people adapt their grip force to the weight of a lifted object; grip force is larger for heavier objects than it is for lighter objects (Gordon *et al*., 1993; Johansson and Westling, 1988). When lifting an object of unknown weight with a precision grip, individuals will initially generate a large grip force to ensure that the object does not slip. The grip force is then relaxed until tiny micro-slips occur; this results in an automatic increase in grip force within 60-90 ms to a level slightly above that required to prevent slip (Westling and Johansson, 1984). When the weight of the object can be predicted by the subject, grip force adjustments are anticipatory; both the rate of rise of grip force during the loading phase and the grip force during the hold phase are scaled to the expected weight of the object (Johansson and Westling, 1984). The adaptation of grip force development to an object's weight during the loading phase is based on memory from previous lifts because information about the object's weight is not available until lift-off (Gordon *et al*., 1991c, 1993; Johansson and Westling, 1988).

2.4.2.3. Adaptation to Other Physical Properties of the Object

A number of sensory-based mechanisms, including visual and haptic information, are involved in the anticipatory control of force output. This is important because we handle objects of different size, shape, weight, and density during everyday activities.

Object size cues acquired both visually and haptically influence the grip and load forces during the loading phase (Gordon *et al*., 1991a, b). By lifting boxes of various sizes having the same weight, it was demonstrated that individuals generate increased grip and load force rates for larger objects; this suggests that a size-weight relation is used by the CNS for anticipatory force control when grasping similar objects of different size (Gordon *et al*., 1991c). It has also been shown that when manipulating unfamiliar objects, individuals apparently use a default density estimate in the range of common densities to initially generate an appropriate grip force (Gordon *et al*. 1993). After several lifts, an adequate memory representation is formed for anticipatory control of force parameters.

2.4.3. Control of Prehension During Object Transport

Moving an object requires the acceleration of the object from rest and then decelerating it to a stop at the goal location. This results in significant inertial forces acting on the object in addition to the force of gravity. Because we grip with only a small safety margin to counteract the gravitational force acting on an object, the added inertial load requires an increase in grip force or the object will slip. Therefore, the forces due to accelerating and decelerating an object during transport endanger the stable grasp of an object (for a review, see Wing, 1996).

2.4.3.1. Arm Movements

During horizontal arm movements, the grip force increases with or slightly before the increase in load force at the start of the movement; the time at which the grip force reaches its maximum value coincides with that of the maximum load force (Flanagan and

Wing, 1993; Flanagan et al., 1993). The temporal synchronization and correlation of the magnitudes of the grip and load forces vary consistently in response to changes in the inertial load forces. This demonstrates that there is an anticipatory modulation of grip force to compensate for the acceleration-dependent inertial load forces that act on hand-held objects during voluntary movements.

Stable grip and load force patterns are also seen when performing vertical arm movements (Flanagan and Wing, 1993; Flanagan et al., 1993). However, there are differences in the grip and load force patterns observed when comparing upward and downward movements. In upward movements, grip force increases during the acceleratory phase at the start of the movement due to the immediate rise in load force. During downward movements, gravity causes an object to move downward without the need for active acceleration; as a result, the load force in a downward movement is initially low and the grip force increase is delayed until the deceleration phase. However, when a downward movement is made rapidly, a relatively large load force is developed in the initial phase; this results in an earlier rise in grip force and larger grip force magnitude in the deceleration phase. This implies that the timing of the increase in grip force is associated with the rise in the load force and not simply with the onset of arm movement (Wing, 1996). These results regarding the coupling of grip and load forces demonstrates that the programming of grip force is an integral part of the process of planning arm movements (Flanagan and Wing, 1993; Flanagan et al., 1993; Wing, 1996).

2.4.3.2. Whole-Body Movements

The coupling of grip and load forces of a hand-held object during whole-body motions has been examined in a wide range of activities such as locomotion (Kinoshita *et*

al., 1996), stepping up and down (Flanagan and Tresilian, 1994), jumping up and down (Wing, 1996), and pushing/pulling movements (Wing *et al*., 1997). It was demonstrated that grip force changed in response to variations in load force; grip force increased when load force increased. In addition, increases in grip force and ground reaction force (GRF) preceded the rise in load force; also, the rates of change in grip force and GRF were correlated both prior to the increase in load force and at the onset of load force. These findings suggest that there is a task-related functional synergy between grip force and whole-body movements (Wing, 1996; Wing *et al*., 1997).

2.4.4. Control of Prehension During Object Manipulation

In dynamic grasping four forms of manipulation can be considered (Elliott and Connolly, 1984): (1) *fixed contacts* – the contacting locations between the hand and object remain constant as motion is imparted to the object using coordinated manipulation, e.g., writing with a pen or screwing a lid; (2) *rolling contacts* – the contacting locations between the hand and object roll past one another while imparting rolling motion to the object, e.g., screwing a small nut or winding a watch; (3) *sliding contacts* – the contacting locations slide relative to one another imparting sliding motion to the object, e.g, squeezing a rubber bulb or syringe; and, 4) *repositioning* or *regrasping* – motion is imparted to the object by relocating the hand's contacting points on the object, e.g., turning a dial or turning a pen end over end.

Manipulative tasks may be divided into two types: manipulating *passive* objects (to move or reposition mechanically predictable, stable objects like a cup or pen) or *active* objects (to manipulate mechanically unpredictable objects, such as holding a dog's leash or operating a power tool) (Johansson *et al*., 1992a, b, c; for reviews, see

Johansson, 1996; Johansson and Cole, 1994). During the manipulation of passive objects, the control of muscle commands is based on anticipatory parameter control; we rely on internal representations of the object's properties based on previous manipulative experiences. Johansson and colleagues (Johansson and Cole, 1992, 1994) suggested somatosensory afferent signals intervene only intermittently, according to an 'event driven' control policy. In contrast, during the manipulation of active objects anticipatory control strategies are of limited use due to the unpredictable load forces and continuously changing physical characteristics of the object. The control of grip force must rely more regularly on somatosensory input. Grip forces appear to be automatically regulated according to fluctuations in the magnitude and rate of imposed load forces (Johansson *et al*., 1992a, b, c).

2.4.5. INDIVIDUATED FINGER MOVEMENTS

Independent finger movements are required for prehension and manipulation. It was previously mentioned in Section 2.2 that the fingers are primarily flexed/extended by the extrinsic muscles of the hand. Several of the extrinsic muscles give off multiple tendons that move more than one finger when contracted. As a result, each muscle influences several fingers; therefore, an individual finger movement cannot be produced by only one flexor or extensor muscle. Instead, the movement of a finger is produced by the combined activity of a set of extrinsic muscles.

2.4.5.1. Interdependence of Finger Movements

The fingers of the hand are often assumed to move independently. However, when a person produces movement or force in one or more digits, there is simultaneous

motion (Fish and Soechting, 1992; Santello *et al*., 1998; Soechting and Flanders, 1992) or force production (Zatsiorsky *et al*., 1998, 2000) in the other digits of the hand. This involuntary force production by fingers not explicitly involved in a force production task (*enslaving*; Zatsiorsky *et al*., 1998), can potentially be due to: (1) peripheral mechanical coupling, (2) multi-digit motor units in the extrinsic flexor and extensor muscles of the hand, and (3) a central neural mechanism.

Biomechanical interconnections between the digits come from many sources. The fingers are flexed and extended primarily by the extrinsic muscles, whose bellies lie in the forearm and whose tendons pass across the wrist to insert on the digits. Unlike most muscles elsewhere in the body, several of these muscles give off multiple insertion tendons. Four extrinsic muscles give off only a single tendon to a single digit: FPL, EPL, EIP, and EDM; three muscles each give tendons to all four fingers: FDP, FDS, EDC. The tendons of the fingers in the hand are frequently interconnected by tendinous or fascia-like anatomical structures (Fahrer, 1981; Kilbreath and Gandevia, 1994; Leijnse, 1997; Leijnse *et al*., 1992, 1993). Well-known examples are the juncturae tendinum between the EDC (Fahrer, 1981; Kaplan, 1984; von Schroeder *et al*., 1990) and connections within the FDP (Fahrer, 1981; Malerich *et al*., 1987; Verdan, 1960). The interconnections between tendons often result in finger coordination difficulties in musicians, especially in pianists and string players, when highly independent finger movements are required (Leijnse, 1997; Leijnse *et al*., 1992, 1993).

Finger movements may also be coupled by the organization of motor units in the multitendoned extrinsic finger muscles: FDP, FDS, and EDC. For example, many single motor units have been found to act on independent tendons to two digits (Schieber *et al*.,

1997). In addition, the motoneuron pools innervating different finger muscles receive considerable shared central input. Bremner *et al*. (1991a, b) have demonstrated that intrinsic and extrinsic muscles acting on different fingers receive shared inputs. Also, enslaving could be caused by muscle fibers activated within the deep flexor of one finger, but inserted into the deep flexor of another finger (Kilbreath and Gandevia, 1991, 1992, 1994). The coactivation force will then be proportional to the number of coactivated muscle fibers inserted into the other tendon.

The combined action of several fingers may also be due to diverging central commands. The primary motor cortex M1 is an essential part of the brain for the production of individuated finger movements. The *labeled-line* hypothesis suggests that movements of different fingers are controlled from spatially separate regions of M1 (Schieber, 1996). However, studies (Poliakov and Schieber, 1999; Schieber, 1999; Schieber and Hibbard, 1993; Schieber and Poliakov, 1998) have indicated that the somatotopy of M1 is not as spatially segregated as might be suggested by the homunculus of Penfield (Penfield and Rasmussen, 1950) or simiusculus of Woolsey (Woolsey *et al*., 1951) (for reviews, see Sanes and Schieber 2001; Schieber, 1990, 1996). First, there is *convergence* of output from large, overlapping cortical territories onto single muscles (Andersen *et al*., 1975; Kwan *et al*., 1978; Penfield and Boldrey, 1937; Sato and Tanji, 1989; Woolsey *et al*., 1951, 1979). Second, *divergence* of output from single M1 neurons to multiple muscles has been shown both anatomically (Shinoda *et al*., 1981) and physiologically (Cheney and Fetz, 1985; Buys *et al*., 1986). Third, extensive horizontal *interconnections* between subregions within the M1 hand area have been demonstrated (DeFelipe *et al*., 1986; Huntley and Jones, 1991; Keller and Asanuma, 1993). Fourth,

activation is distributed throughout the M1 hand area whenever any finger movement is made (Sanes *et al*., 1995; Schieber and Hibbard, 1993).

Though all three previously discussed factors may contribute to enslaving effects, Zatsiorsky *et al*. (2000) found that these effects cannot be explained solely by either peripheral mechanical coupling or multi-digit motor units in the extrinsic flexor and extensor muscles of the hand. It was suggested that a widespread neural interaction among the structures controlling the flexor muscles in the hand was a fundamental mechanism of finger force enslaving.

2.4.5.2. Independence of Finger Movements

Independent finger action underlies our ability to grasp and manipulate objects. Given the factors pertaining to the interdependence of finger action discussed previously, the question arises: How can we produce movement of or force in one digit without producing equivalent action in the other digits?

One possible answer is that the intrinsic muscles of the hand, rather than the extrinsic muscles, are responsible for flexing/extending only one finger at a time (Schieber, 1996). However, the intrinsic muscles act mainly in controlling the configuration of a given digit's phalanges at the MCP, PIP, and DIP joints, and the abduction/adduction motion about the MCP joint (Landsmeer and Long, 1965; Long, 1968; Long and Brown, 1964); the extrinsic muscles control the overall flexion/extension of the digits (Li *et al*., 2000; Long *et al*., 1970). Therefore, the intrinsic muscles cannot account for individuation of flexion/extension finger movements (Schieber, 1996).

A second possible answer is that each multitendoned finger muscle, though nominally a single muscle, might have multiple functional subdivisions, with a different

subdivision serving the tendon to each finger (Schieber, 1996). Although anatomically a single muscle, functionally the nervous system could turn these different subdivisions on and off like different muscles. In macaque monkeys, each of the multitendoned extrinsic finger muscles consists of multiple regions of muscle fibers innervated by different nerve branches (Serlin and Schieber, 1993). One such muscle is the FDP. In both monkeys and humans, various regions of FDP can be activated differentially under voluntary control from the nervous system (Fleckenstein *et al*., 1992; Jeneson *et al*., 1990; Kilbreath and Gandevia, 1994; Schieber, 1993; Schieber *et al*., 2001). Still, available evidence of functional subdivisions in the multitendoned muscles is inadequate to account for individuation of flexion and extension finger movements (Schieber, 1996).

A third possible answer is that different actions in which one finger moves or produces force more than others could be produced by different combinations of activity in a set of multi-tendoned muscles (Schieber, 1996). Schieber (1995) addressed this possibility by recording EMG activity from the muscles of the forearm as rhesus monkeys performed individuated flexion and extension movements of each digit of the hand and of the wrist. It was demonstrated that during movements of different fingers, a given muscle could act as an agonist, antagonist, or stabilizer of the digit it serves. Furthermore, during a given finger movement, several different muscles typically were active. These results indicate that individuated finger movements and/or force production are not produced by independent sets of muscles acting on each digit, but rather by the activity of several muscles, many of which act on more than one digit, combined such that the net effect is movement of or force production by one digit more than others (Schieber, 1996).

2.4.6. HAND SYNERGIES

One of the major issues in the control of the hand is whether the CNS is concerned with the control of each individual muscle or whether it combines muscles into groups and exerts control over each group as a unit rather than over the elements of the group (for a review, see Hepp-Reymond *et al*., 1996). According to Latash (1998), a synergy is a combination of control signals to a number of muscles whose purpose is to assure a certain movement or preserve a certain posture. Therefore, the elements that comprise a synergy are constrained to act as a single unit, leading to a simplification of the central command to the musculoskeletal system by reducing the number of degrees of freedom that have to be controlled (Bernstein, 1967).

In everyday activities, the fingers usually work in synergy. One of the characteristic features of a synergy is inter-compensation, i.e., the ability to compensate for perturbations (Bernstein, 1967; Turvey, 1990). It has been demonstrated that the fingers compensate for each other when an external perturbation is applied (Cole and Abbs, 1987). The kinematic responses of the thumb and index finger to a load-induced extension of the thumb during a rapid precision grasp were studied. Despite the loads that extended the thumb, contact between the finger and thumb was attained nonetheless. Cole and Abbs (1987) hypothesized that afferent information generated by the perturbation of the thumb during a grasp movement can influence the activity of intrinsic and extrinsic muscles to yield functional compensations in the closing movement.

Inter-compensation between the fingers has also been reported when trial-to-trial variability was observed (Cole and Abbs, 1986). Thumb and index finger kinematics were examined for multiple repetitions of a rapid pinching movement of the index finger

and thumb. It was found that most kinematic features of the grasp varied considerably across trials. However, this variability was not random; fingertip path adjustments acted to minimize variations in the point of contact of the index finger on the thumb. Cole and Abbs (1986) theorized that the variable movements of the index finger and thumb and the associated contact force were generated as a single action.

Finally, error compensation by a redundant set of fingers has been exhibited when a self-perturbation is induced (Latash *et al*., 1998). Subjects were instructed to produce a given force with three fingers acting in parallel and then to perform a series of taps at 2 Hz with one of the fingers. Analysis of individual finger force profiles demonstrated that during index and middle finger tapping in all subjects and during ring finger tapping in 50% of the subjects, a decrease in the force of the tapping finger was accompanied by a simultaneous increase in the force produced by the non-involved fingers. Latash *et al*. (1998) interpreted the data as a result of a feedforward central mechanism leading to parallel changes in the forces produced by fingers united into a coordinative structure.

The variability of individual finger forces in pressing tasks using all four fingers simultaneously has been used to demonstrate the existence of synergies (Li *et al*., 1998b). When the goal was to produce maximal total force, it was found that: (a) a negative correlation existed between maximal finger forces in multiple trials, and (b) the variance of the total force produced was smaller than the sum of the variances of the individual finger forces. These two variances should be equal if individual finger forces vary independently; hence, the latter result suggests that the individual finger forces were negatively correlated on average. The results of these studies demonstrate that synergies are used by the CNS to simplify the control of the hand by eliminating redundant DOFs.

2.5. THE MOTOR REDUNDANCY PROBLEM

Bernstein (1967) formulated the main problem of the control of human voluntary movement as the elimination of motor redundancy. Originally, the problem was formulated with respect to the discrepancy between the number of kinematic DOFs of the body and the number of external mechanical constraints imposed upon the system. The human body has 244 kinematic DOFs (Kuo, 1994; Morecki *et al*., 1984). Since only six DOFs are required to specify the position and orientation of a body segment in space, there are an infinite number of ways of performing a movement task. It should be noted that the essential features of the redundancy problem exist at all levels of movement production, such as motor units, muscles, joints, etc. The Bernstein problem has been addressed at both the kinematic and kinetic levels of the musculoskeletal system. When this problem is examined at the kinematic level it is referred to as the DOFs problem, while the problem at the level of kinetics is called the force sharing problem.

At present, we are unable to understand the means by which the CNS coordinates redundant DOFs to perform a motor task. Because of this, several different modeling, analytical, and experimental approaches have been used to study the DOFs problem, such as the equilibrium-point hypothesis, dynamical systems theory, optimization, and synergies. Of particular importance in these methods are the large number of DOFs, and whether this apparent redundancy is a help or a hindrance to the CNS (Latash, 2000).

One proposed solution to the DOFs problem that has received a great deal of attention is the equilibrium-point hypothesis (for reviews, see Bizzi *et al*., 1992; Feldman, 1986; Latash, 1993). According to this hypothesis, the spring-like properties of muscle are responsible for generating the necessary joint torques, thus eliminating the need for

detailed planning of limb trajectories. The stretch reflex thresholds for opposing muscles are centrally adjusted; the point at which the agonist-antagonist tensions balance out establishes an equilibrium-point for the system. Movement is generated by shifting the equilibrium-point between the length-tension curves of opposing muscles. To create an equilibrium-trajectory, the CNS must transform the planned movement into a series of different equilibrium positions and muscle stiffnesses. It is unlikely that the equilibrium-point control hypothesis can solve the DOFs problem, since it is unclear how equilibrium points are chosen (Rosenbaum *et al*., 1996).

A second approach to resolve the DOFs problem is based on dynamic systems theory (for reviews, see Schöner and Kelso, 1988; Sternad, 1998; Turvey, 1990). This method suggests that interactions between effectors lead to coupling in rhythmical multilimb movements. The first examples of extremity coupling in humans and fish were presented by von Holst (1939/1973). More recent studies have shown that coupling exists in bimanual finger coordination (Haken *et al*., 1985; Semjen and Ivry, 2001; Yaminishi *et al*., 1980). If two independent effectors of a system are coupled, then linkages between these effectors will reduce the number of DOFs of the system that need to be independently controlled. However, it is doubtful that coupling can solve the DOFs problem (Rosenbaum *et al*., 1996). First, if coupling eliminated the DOFs problem for a task with *n* DOFs, it would not be possible to perform a task with more than *n* DOFs. Second, it is incorrect to suppose that linkages exist for the purpose of reducing DOFs.

A third methodology used to examine to the DOFs problem is based on optimizing a cost function during voluntary movements (for reviews, see Latash, 1993; Nelson, 1983; Seif-Naraghi and Winters, 1990; van der Helm, 2000). The choice of the

cost function is rather arbitrary, and is typically based on movement kinematics (velocity, acceleration, jerk), movement kinetics (joint torque), energy, effort, or comfort. This approach is based on an assumption that the CNS chooses one cost function over the others. To date, none of these cost functions have led to a breakthrough in understanding how the CNS controls movements. While many of these cost functions predict movement patterns that resemble those observed in experiments, this does not mean that the CNS minimizes or maximizes a cost function (Latash, 1993). Rather, it suggests that the solutions chosen by the CNS do not violate any of these principles to a large degree. Thus, the actual priorities of the CNS still remain unknown (Latash, 1998).

Another common approach to the DOFs problem relies on the concept of synergies (for reviews, see Latash, 1993, 1998; van der Gon *et al*., 1991). Synergies are combinations of control signals whose purpose is to assure a certain movement of a body segment (Latash, 1993, 1998). A major issue in motor control theory is whether the CNS is concerned with the control of each individual muscle, or whether it combines muscles into groups and exerts control over the whole group. According to Bernstein (1967), the CNS solves the problem of many DOFs by forming functional synergies or classes of movement patterns. Since the musculoskeletal system possesses multiple DOFs, a given movement can be achieved with various muscle activation patterns. If muscle groups with spatially and temporally synchronous activation patterns are observed in a task, this would support the existence of fixed muscle synergies (Hepp-Reymond *et al*., 1996).

2.5.1. Force Sharing Among Synergistic Muscles

The determination of the forces generated by individual muscles during human voluntary movement has become one of the most important research problems in

biomechanics and motor control. Norman (1989) stated that: "In my opinion, the single most important problem in the study of human motion is the development of accurate, noninvasive methods of calculating individual muscle and ligament force-time histories during normal human movements." The force-time histories of the individual muscles contributing to a movement task has been referred to as *force sharing* among muscles (Herzog, 1996; Herzog and Leonard, 1991; Li *et al*., 1998a, b; Prilutsky *et al*., 1994; Zatsiorsky *et al*., 1998).

The force sharing problem is classified as an ill-posed problem (Latash, 1996, 1998). An ill-posed problem exists when a central controller is supposed to make a choice from a theoretically infinite number of solutions while the criteria for making a choice are not explicitly stated. Such problems are similar to attempts to solve one equation with two unknowns; the equation has an infinite number of solutions. The result is a biomechanically underdetermined system. For example, when a joint is spanned by two or more synergistic muscles, there are an infinite number of different combinations of muscle forces that can produce a desired movement or joint torque. The question of how a large number of muscles generate a required force or joint torque has received considerable attention (Gielen *et al*., 1995; Herzog, 1996, 2000; Hogan *et al*., 1987; Kuo, 1994; Prilutsky, 2000; Zajac, 1993). A variety of approaches have been developed to examine force sharing among synergistic muscles, such as the reduction method, electromyography-to-force processing models, direct tendon force measurement, static and dynamic optimization, and neural network designs (for reviews, see Crowninshield and Brand, 1981b; Herzog, 1996; van den Bogert, 1994; Zajac and Gordon, 1989; Zajac and Winters, 1990). A discussion of these methods will now be presented.

2.5.2. REDUCTIONISM

The partitioning of muscle and joint forces acting on the musculoskeletal system is referred to as the *distribution problem* (An *et al.*, 1995; Crowninshield and Brand, 1981b). Unfortunately, determining these forces is not a straightforward process. In the calculation of intersegmental forces, the number of unknown variables (muscle and joint constraint forces) usually exceeds the number of equations describing the system. The result is a biomechanically underdetermined system, in which there are fewer system equations than unknowns (Herzog and Binding, 1999). This is due to the redundancy of the musculoskeletal system, in which more than one muscle often spans a given joint.

A common strategy used to solve an underdetermined system is to reduce the number of unknown forces until the number of equations and unknown forces is the same (An *et al.*, 1995; Crowninshield and Brand 1981b, Herzog and Binding, 1999). This is usually accomplished by combining different muscles with similar functions into one muscle group and is referred to as the reduction method. The approach has been used to estimate muscle forces acting at the ankle joint (Burdett, 1982; Procter and Paul, 1982), knee joint (Fuller and Winters, 1993; Morrison, 1968, 1970), hip joint (Fuller and Winters, 1993; Paul, 1965), trunk (Chaffin, 1969; van Dieën and de Looze, 1999), and fingers (Berme *et al*., 1977; Toft and Berme, 1980). The major weakness of this method is that although it provides a mathematically unique solution for the forces in a muscle group, the forces produced by individual muscles are not determined.

2.5.3. ELECTROMYOGRAPHY

A second approach for examining force sharing among synergistic muscles involves the use of electromyography (EMG) to predict muscle forces (for reviews, see

Basmajian and de Luca, 1985; Dowling, 1997; Hof, 1997; Perry and Bekey, 1981). The general theory behind the EMG methodology is that the net moment of force at a given joint can be estimated accurately and reliably if the EMG is suitably processed to reflect the activation of each muscle crossing the joint and if this activation is modulated properly according to the known characteristics of muscle mechanics (Dowling, 1997). The first step involves estimating the activation of an individual muscle using the EMG signal and determining the kinematics of each joint that the muscle crosses. The second step involves the input of this data into a Hill-type muscle model to predict the force of that muscle. The third step combines the predicted forces of each individual muscle with a model that contains the moment arm information and passive structural contributions to predict the net moment of force about that joint.

The use of muscle models for EMG-to-force processing was first systematically evaluated by Hof and van den Berg (1981a, b, c, d). They developed a Hill-type muscle model used to quantify the contributions of the gastrocnemius and soleus muscles to the total plantarflexion moment of the ankle joint. EMG-driven biomechanical models used to examine force sharing have subsequently been developed for the ankle (Hof *et al*., 1987; Olney and Winter, 1985), knee (Lloyd and Buchanan, 1996; Olney and Winter, 1985), lumbar spine (McGill and Norman, 1986; Nussbaum and Chaffin, 1998; Thelen *et al*., 1994), shoulder (Laursen *et al*., 1998), elbow (Buchanan *et al*., 1998), and wrist (Buchanan *et al*., 1993).

The advantages of this method are that it uses a dynamic muscle model, takes advantage of all available information, does not depend on imperfect joint torque calculations via inverse dynamics, and is computationally simple enough to be used in

real time (Zajac and Winters, 1990). The disadvantages of this technique are that it relies extensively on imperfect EMG signals and the parameter values of the musculoskeletal model (Zajac and Winters, 1990).

2.5.4. Direct Measurement of Tendon Force

A third method used to examining force sharing among synergistic muscles involves the direct measurement of tendon force (for reviews, see Gregor and Abelew, 1994; Komi, 1990; Komi *et al*., 1992). One approach is to measure the strain, which is proportional to force, in a buckle-shaped metal transducer and through which the tendon passes (An *et al*., 1990; Barry and Ahmed, 1986). A second option involves the use of a liquid metal strain gauge placed in parallel with the tendon (Meglan *et al*., 1988; Seireg and Gray, 1978). Another method is to use optic fiber as a transducer of tendon forces (Finni *et al*., 1998; Komi *et al*., 1996). This method is based on light intensity modulation by mechanical modification of the geometric properties of the optic fiber.

The use of direct experimental force measurements to study the interactions of muscles during movement was pioneered by Walmsley *et al*. (1978). Walmsley and colleagues studied the interaction between cat soleus and gastrocnemius muscles in a variety of locomotor conditions. This study was followed up with similar experiments (e.g., Abraham and Loeb, 1985; Hodgson, 1983; Smith *et al*., 1980), and together these studies have given a better understanding of the force sharing between soleus and gastrocnemius muscles for different movement tasks. More recently, direct muscle force measurements in cats were expanded to all muscles comprising a functional group (gastrocnemius, soleus, and plantaris muscles) and a corresponding functional antagonist (tibialis anterior) in order to increase the understanding of force sharing among agonist

and antagonist muscles for movements ranging from slow walking to trotting (e.g., Herzog and Leonard, 1991; Herzog *et al*., 1993; Herzog, 1998).

Direct measurement of tendon force in humans has been performed in a variety of activities. For example, Achilles tendon forces have been measured during locomotion (Finni *et al*., 1998; Komi *et al*., 1984; Komi *et al*., 1987), jumping (Finni *et al*., 2000; Fukashiro *et al*., 1993, 1995), and cycling (Gregor *et al*., 1987; Gregor *et al*., 1991). Tendon forces in the hand and wrist have also been directly measured (for a review, see Dennerlein, 2000). Mendelson *et al*. (1988) placed transducers on the tendons of the extensor carpi radialis brevis and longus for the simultaneous measurement of strength of each individual muscle during voluntary and/or electrically stimulated extension of the wrist. The forces of the FPL, FDS, and FDP tendons of the index finger generated during passive and active motion of the wrist and fingers were recorded in patients operated on for treatment of carpal tunnel syndrome by Schuind *et al*. (1992). Tendon forces up to 12.0 kgf were recorded during tip pinch, with a mean applied pinch force of 3.5 kgf. Dennerlein *et al*. (1998) measured the tension of the FDS tendon of the middle finger in patients undergoing carpal tunnel release surgery while the force applied by the fingertip ranged from 0 to 10 N. The average ratio of the tendon tension to the fingertip contact force ranged from 1.7 to 5.8. Most recently, the FDS tendon forces of the middle finger were recorded during rapid tapping on a computer keyswitch while patients underwent carpal tunnel release surgery (Dennerlein *et al*., 1999). The average maximum tendon forces ranged from 8.3 to 16.6 N.

The value of direct measurement of tendon force is obvious: it provides the unique ability to study muscle function *in vivo* and takes movement analysis one step

closer to the neuromuscular system (Gregor and Abelew, 1994). However, there are several limitations regarding direct tendon force measurement. First, the force measures of a transducer placed on a tendon are questionable, since the transducer is in an environment that is influenced by many other structures surrounding the joint (Hahs and Stiles, 1989). Second, direct force measurement can only be performed on selected muscle tendons; (Gregor and Abelew, 1994). Third, tendon response to the force transducer and the length of time the transducer is implanted can influence the output of the transducer (Gregor and Abelew, 1994). Despite these limitations, direct measurement of tendon forces has contributed to our understanding of the control of the neuromuscular and musculoskeletal systems (Gregor and Abelew, 1994; Herzog, 1996, 2000).

2.5.5. OPTIMIZATION

The most common approach used to study the force distribution and sharing problems in human movement is mathematical optimization (for reviews, see Latash, 1993; Nelson, 1983; Prilutsky and Zatsiorsky, 2002; Seif-Naraghi and Winters, 1990; Stein *et al*., 1986; van der Helm, 2000; Winters, 2000). Optimization is the process of maximizing or minimizing a desired objective function while satisfying the prevailing constraints (Chong and Zak, 1996). The general concept of optimization in human movement was initially formulated by Weber and Weber (1836), who stated that man walks in “the way that affords us the slightest energy expenditure for the longest time and with the best results.” The use of optimization to examine force sharing among synergistic muscles first appeared about 35 years ago. MacConaill (1967) defined a ‘Principle of Minimal Total Muscular Force’ which stated that “no more total muscular force is used than is both necessary and sufficient for the task to be performed, whether

this be one of supporting some weight or carrying out a movement, the resistance to which may vary from zero upwards." Optimization theory has been identified as a useful tool for exploring goal-directed behavior (Hogan and Winters, 1990). Typically, optimization techniques are used for two reasons in the study of the control of human movement: 1) to solve the problem of force sharing among synergistic muscles, and 2) to generate movement from the perspective of the neuromotor system (Zajac and Winters, 1990). The classifications static optimization and dynamic optimization, respectively, have been used to distinguish between these approaches (Zajac and Gordon, 1989).

2.5.5.1. Static Optimization

Static optimization refers to the process of minimizing or maximizing the costs/benefits of some action for one instant in time only (Challis, 1999) (for reviews, see An *et al*., 1995; Crowninshield and Brand, 1981b; Tsirakos *et al*., 1997). Static optimization methods have been used to estimate muscle forces for the knee (e.g., Dul *et al*., 1984a, b; Kaufman *et al*., 1991a, b), hip (e.g., Crowninshield *et al*., 1978; Hoek van Dijke *et al*., 1999; Pedersen *et al*., 1997), lumbar spine (e.g., Bean *et al*., 1988; Gracovetsky *et al*., 1977; Schultz *et al*., 1983), shoulder (e.g., Karlsson and Peterson, 1992; Nieminen *et al*., 1996; van der Helm, 1994), elbow (e.g., An *et al*., 1989; Crowninshield, 1978; Yeo, 1976), wrist (e.g., Penrod *et al*., 1974), and fingers (e.g., Chao *et al*., 1989; Dennerlein, 2000).

In order to solve an optimization problem, it must be formulated in the following way (An *et al*., 1995): (1) define the cost function, (2) identify the constraint functions, (3) specify the design variables, and (4) set the appropriate bounds for the design variables. This problem can be summarized as follows:

Minimize

$$J = f(x_1, x_2, \ldots, x_n) \tag{2.1}$$

subject to

$$g_j(x_1, x_2, \ldots, x_n) = 0 \quad (j = 1, 2, \ldots, m) \tag{2.2}$$

and

$$0 \leq x_i \leq U_i \quad (i = 1, 2, \ldots, n) \tag{2.3}$$

where J is the optimal criterion (cost function), the function g represents certain equality constraint relationships, x_i stands for the unknown muscle and joint forces, and U_i represents the upper bounds of the muscle and joint forces. These variables may be subject to inequality constraints. The optimization problem can be solved mathematically using a variety of numerical techniques such as the Simplex algorithm for linear objective functions (Dantzig, 1963), the direct search method of Hooke and Jeeves (1961), the Downhill Simplex technique (Nelder and Mead, 1965), and sequential quadratic programming for non-linear objective functions (Schittowski, 1985).

The choice of objective function is very important in static optimization, because its minimization or maximization determines the solution to the problem. Indeed, the results are very sensitive to the choice of cost function (Challis and Kerwin, 1993). An *et al*. (1995) suggest that the objective function must be related to the movement task. Unfortunately, the cost function to be minimized cannot be known *a priori* and may vary from person to person depending on the demands of the task (Vaughan *et al*., 1982). The objective functions used to study the force sharing problem generally fall into two classes: linear and nonlinear optimization criteria.

The estimation of muscular forces using linear objective functions has been obtained by minimizing the sum of muscle forces (e.g., Pedotti *et al*., 1978; Seireg and Arvikar, 1973, 1975), by minimizing the muscle stress (e.g., An *et al*., 1984, 1989; Bean *et al*., 1988; Crowninshield, 1978; Crowninshield and Brand, 1981a), or by minimizing the overall muscle activation level (Kaufman *et al*., 1991a, b). Linear objective functions have been criticized for being incapable of predicting coactivation of synergistic muscles and that the solution is highly related to the number of imposed constraints (Crowninshield and Brand, 1981b; Tsirakos *et al*., 1997; Prilutsky and Zatsiorsky, 2002).

To overcome the limitations of linear cost functions, nonlinear optimization criteria have been used. Nonlinear objective functions can predict coactivation of muscles, even without the use of additional constraints. Examples of nonlinear objective functions include minimizing the sum of squared shear stresses (Gracovetsky *et al*., 1977), minimizing the sum of muscle forces raised to some power (e.g., An *et al*., 1984; Challis and Kerwin, 1993; Collins, 1995; Dul *et al*., 1984a, b; Pedotti *et al*., 1978), or minimizing the sum of muscle stresses raised to some power (e.g., Challis and Kerwin, 1993; Collins, 1995; Crowninshield and Brand, 1981b; Dul *et al*., 1984a, b; Kaufman *et al*., 1991a, b). Nonlinear optimization improves muscle force predictions, but this method is usually more involved and less efficient than linear programming (An *et al*., 1995).

There are several advantages to using static optimization methods to examine the force sharing problem: (1) they are computationally efficient compared to dynamic optimization methods; (2) the contact forces between the body and the environment are typically measured, so the equations can be solved in an efficient distal-to-proximal

sequence; and (3) they provide information regarding muscle force and joint contact loading (Winters, 1995). However, these methods provide limited insight into the underlying neuromuscular control strategy because the performance criterion is solved only at a given instant in time (Zajac and Gordon, 1989; Zajac and Winters, 1990). In addition, it is not easy to identify an objective criterion for many movements and, if one is found, it is unclear whether the CNS uses the optimization of that particular criterion for muscle coordination (Gielen *et al*., 1995).

2.5.5.2. Dynamic Optimization

Dynamic optimization refers to the process of minimizing and maximizing the costs/benefits of some objective function over a period of time; it is sometimes referred to as optimal control (Challis, 1999) (for reviews, see Pandy, 1990, 2001; Yamaguchi, 1990; Zajac and Winters, 1990; Zajac, 1993). The dynamic optimization process involves using a model that includes the dynamics of a system to find the inputs (e.g., muscle excitation signals) and all outputs (e.g., forces) that maximize the performance of a task as defined by some criterion (Zajac and Gordon, 1989). Criterion such as minimum muscular energy (Alexander, 1997; Cruse, 1986), minimum effort (Hasan, 1986; Lan, 1997), minimum jerk (Flash and Hogan, 1985; Hogan, 1984), minimum torque change (Uno *et al*., 1989), and minimum work (Soechting *et al*., 1995) have been used to define the movement goal in dynamic optimization. Dynamic optimization has been used to analyze such activities as locomotion (Chow and Jacobson, 1971; Davy and Audu, 1987; Pandy and Anderson, 2000), jumping (Pandy and Anderson, 2000; van Soest and Bobbert, 1993; Zajac *et al*., 1984), postural control (Chow and Jacobson, 1972; Kuo, 1995), and arm movements (Lan and Crago, 1994; Oğuztöreli and Stein, 1983).

The advantage of the dynamic optimization approach is that it parallels the problem that must be solved by the CNS during goal-directed voluntary movement (Winters, 1995). Dynamic optimization methods predict the muscle excitation signals that produce a given movement. Zajac and Winters (1990) suggest that forward dynamic simulations provide the preferred method for understanding neuromuscular control strategy. However, there are several limitations to dynamic optimization modeling. First, although the concept of dynamic optimization is simple, implementation is problematic (Zajac and Winters, 1990). Second, analytical solutions are difficult to achieve except for very simple models (Seif-Naraghi and Winters, 1990). Third, considerable computational cost is required, especially for three-dimensional movements (Yamaguchi, 1990). The result is that models must be simplified in many cases.

2.5.6. ARTIFICIAL NEURAL NETWORKS

A relatively new algorithm, known as artificial neural networks, has been gaining widespread use to study the force sharing problem (for reviews, see Bullock *et al*., 1996; Herzog *et al*., 1999; Koike and Kawato, 2000). A network consists of a group of processing units called ‘neurons’ which are interconnected and distributed in layers (Figure 2.9) (Bose and Liang, 1996; Hagan *et al*., 1996). A three-layer network is sufficient to model problems of any degree of complexity (Haykin, 1999). When the network is executed, the input layer receives a number of inputs (EMG signals), and then the hidden and output layer units are progressively executed. Each input to the neurons in the hidden and output layers comes via a connection that has a strength (or weight). Each neuron calculates its activation value by taking the weighted sum of the outputs of the units in the preceding layer. The activation value is passed through a transfer

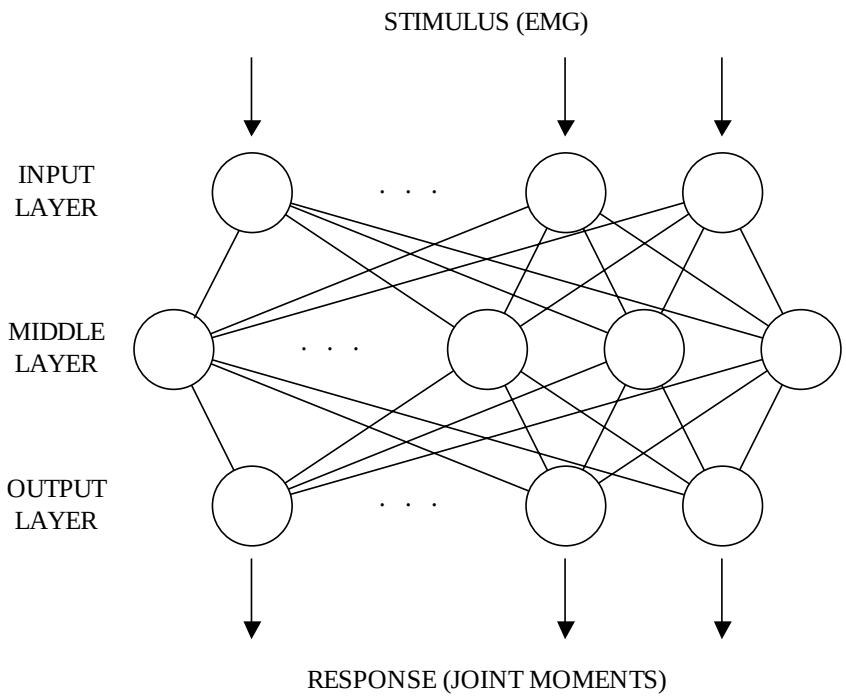


FIGURE 2.8. Basic neural network architecture for a model of human movement. (Adapted from Sepulveda *et al*., 1993)

function to produce the output of the neuron. After the entire network has been executed, the outputs of the output layer represent the output (joint moments) of the entire network.

Artificial neural networks have successfully been used to predict joint moments and muscle forces in cat locomotion (Liu *et al*., 1999; Savelberg and Herzog, 1997), human locomotion (Prentice *et al*., 1998, 2001; Sepulveda *et al*., 1993), static trunk exertion (Nussbaum and Chaffin, 1996; Nussbaum *et al*., 1995, 1997), and upper limb movements (Koike and Kawato, 1995; Luh *et al*., 1999; Shih and Patterson, 1997; Uchiyama and Akazawa, 1999; Uchiyama *et al*., 1998). Multi-finger prehension is also an ideal candidate for using neural networks (Iberall and Fagg, 1996). To date, the vast majority of neural network models pertaining to the hand have analyzed the selection of hand shapes during grasping (Iberall and Fagg, 1996; MacKenzie and Iberall, 1994; Taha *et al*., 1997; Uno *et al*., 1993).

Recently, a neural network model has been developed to predict finger forces during pressing tasks (Zatsiorsky *et al*., 1998) and combined force/torque production during multi-finger prehension (Zatsiorsky *et al*., 2002) (Figure 2.10). The network consists of three layers: (1) the input layer represents a central neural drive; (2) the hidden layer transforms the central drive into an input signal to the muscles serving several fingers simultaneously; and (3) the output layer represents finger force output. In addition, the network features direct connections between the input and output layers that model central command signals to the hand muscles serving individual fingers. As compared to minimal norm optimization, the neural network model predicts force sharing among fingers quite well. Optimization appears to be less efficient than neural network modeling for the following reasons (Zatsiorsky *et al*., 1998): (1) only force sharing is modeled; it does not address force deficit and enslaving; (2) each motor task requires a different optimization procedure; and (3) the cost function does not have anatomical or physiological meaning. The idea behind the network is that force sharing, force deficit,

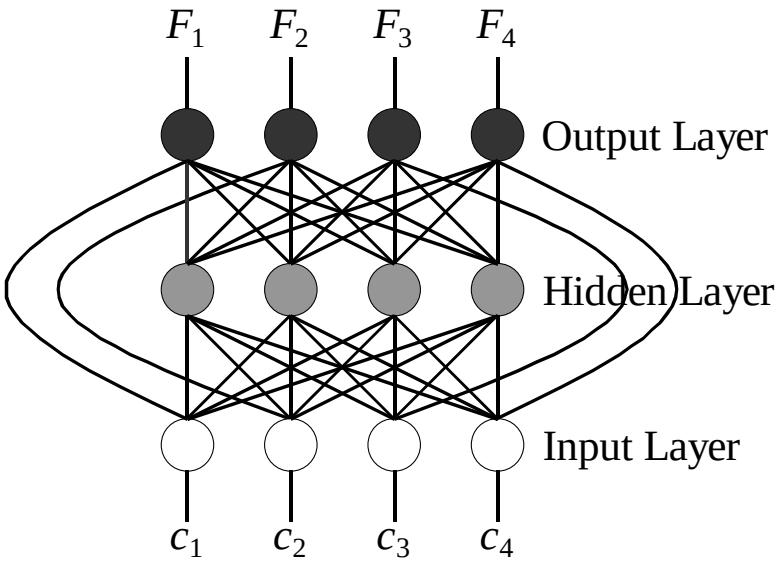


FIGURE 2.9. The basic neural network model. The index, middle, ring, and little fingers correspond to 1, 2, 3, and 4, respectively.

and enslaving are a result of central (at the level of the CNS) and peripheral (at the muscle-tendon level) interconnections among the fingers.

The advantages of artificial neural networks have been identified as being the accurate prediction of *in vivo* skeletal muscle force under dynamic conditions and that they require no input about a muscle's contractile conditions (Herzog *et al*., 1999). However, there are several drawbacks to the neural network approach (Herzog *et al*., 1999): (1) no biological insight about EMG or *in vivo* muscle force production is obtained; (2) force and EMG measurements from the target muscle must be obtained to allow for training of the neural network; and (3) the magnitude of the mathematical procedures underlying neural networks prevents an easy representation of the model in simple or anatomical terms. Overall, neural network modeling has "considerable promise" as a tool to study the force sharing problem in biomechanics and motor control research (Sepulveda *et al*., 1993).

CHAPTER 3

METHODS

3.1. SUBJECTS

Eighteen right-hand dominant males participated in this study. Hand dominance was assessed by determining the subjects' preferred hand for writing. The subjects had the following characteristics (standard deviations in parentheses): age, *M* = 25.0 years (5.0); height, *M* = 178.0 cm (10.0); mass, *M* = 80.0 kg (10.0); hand length (the distance from the distal wrist crease to the tip of the long finger with the hand extended; Garrett, 1971), *M* = 19.0 cm (2.0); and hand breath (the distance across the back of the hand between MCP II and V; Garrett, 1971), *M* = 8.6 cm (0.4). None of the subjects had any previous history of neuropathies or traumas to their upper extremities that might affect performance. All of the subjects gave informed consent according to procedures established by the Office for Regulatory Compliance at The Pennsylvania State University.

3.2. APPARATUS

In this experiment, the subjects were required to stabilize a handle with an attachment that allowed for independent changes of the suspended load and external torque (Figure 3.1). Four uni-axial force transducers (208A03, PCB Piezotronics, Inc., Depew, NY, USA) and a six-axis force/torque transducer (Nano-17, ATI Industrial Automation, Garner, NC, USA) were used to measure the forces of the fingers and thumb, respectively. The finger transducers were connected in series with separate ICP

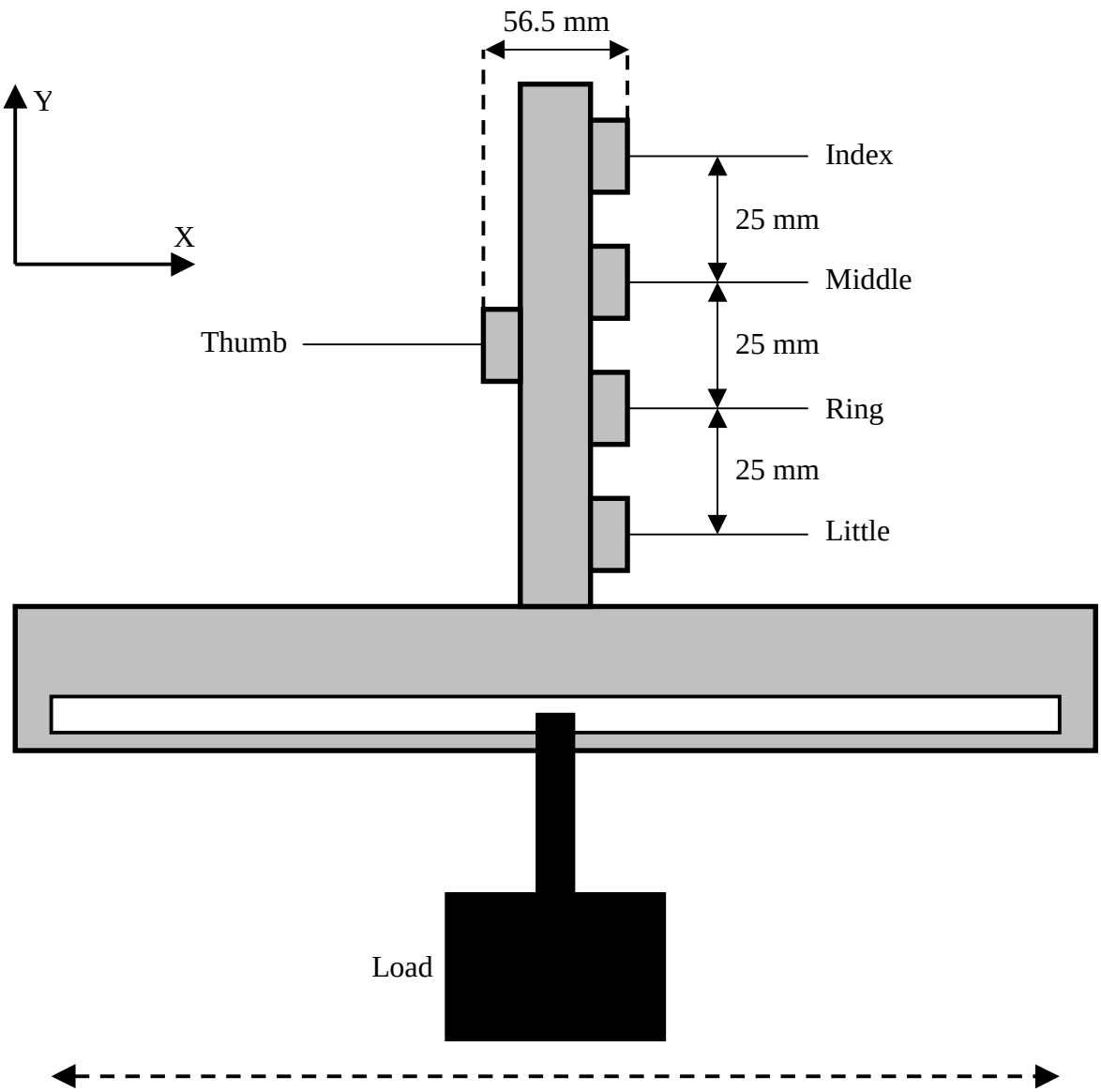


FIGURE 3.1. Schematic drawing of the experimental 'inverted-T' handle/beam apparatus. The force components in the *X* and *Y* directions represent *normal* and *shear forces*, respectively. Subjects were instructed to maintain the handle in a vertically-oriented position using the minimal force possible. (Note: the figure is not drawn to scale.)

power and amplifying units (484B06, PCB Piezotronics, Inc., Depew, NY, USA) (Figure 3.2). The output signals of the finger and thumb force transducers were sent to a 12-bit analog/digital converter (AT-MIO-64F-5, National Instruments, Austin, TX, USA) and a

16-bit ISA bus controller (F/T-16, ATI Industrial Automation, Garner, NC, USA), respectively, interfaced with a personal computer (P5-133, Gateway, Inc., North Sioux City, SD, USA). The resolution of the uni-axial force transducers was 0.54 N, while the resolution of the six-axis force/torque transducer was 0.0021 N and 0.0015 N for normal and shear forces, respectively.

The transducers were mounted on an aluminum handle, which was fixed to the top edge of an aluminum beam and located at the midpoint of the beam. The center points of each of the finger transducers were located 25 mm apart in the vertical direction beginning at a height of 45 mm above the bottom of the handle and ending at a height of 45 mm below the top of the handle. The thumb transducer was located at the midpoint of the handle in the vertical direction. The center points of the index and middle finger transducers were located 37.5 mm and 12.5 mm, respectively, above the center point of the thumb transducer; the center points of the ring and little finger transducers were located 12.5 mm and 37.5 mm, respectively, below the center point of the thumb transducer. Aluminum plates (18.5 mm $\times$ 25.0 mm) were mounted to the transducers to provide a surface for finger contact; the surfaces of the plates were covered with 100-grit sandpaper. The horizontal distance between the grasping surfaces of the finger and thumb transducers was 56.5 mm. A circular level was attached to the top of the handle to monitor the pitch and roll of the handle/beam apparatus. In addition, two vertically oriented rods constrained the motion of both ends of the beam to prevent excessive yaw. A weight hanger was suspended from an eyehook attached to the beam; the total mass of the handle/beam apparatus could be changed by varying the load placed on the weight hanger. A slot running the length of the beam allowed the weight hanger to be moved

along the beam; the external torque exerted on the handle/beam apparatus could be changed by varying the position of the suspended load in relation to the handle. The mass of the handle/beam apparatus by itself (without an external load) was 1.0 kg.

3.3. PROCEDURES

Prior to data collection, subjects washed their hands with soap and water to standardize skin conditions by removing sweat and excessive oil from the skin. Subjects were seated in a chair alongside a table with the upper arm positioned at approximately 45° abduction in the frontal plane and 45° flexion in the sagittal plane (Figure 3.2). In addition, the elbow joint was flexed approximately 45° and the forearm was pronated 90° so that the hand was placed in a natural grasping position. Two lashing straps, located at the proximal and distal end of the forearm, were used to fasten the subjects' forearms to a foam-covered board in order to maintain a constant configuration of the arm throughout the experiment. The arm was positioned so that the hand and wrist extended over the edge of the table to allow for grasping.

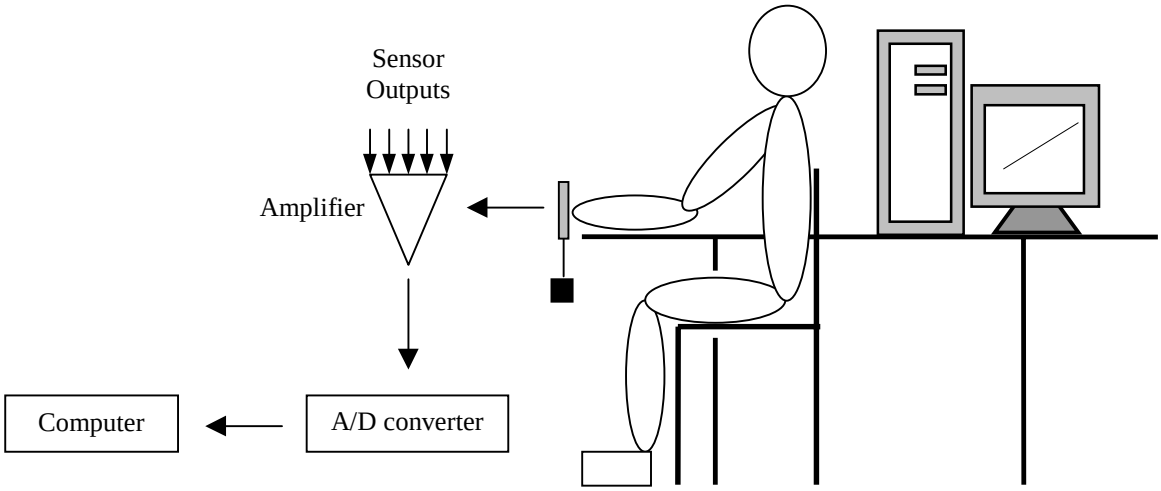


FIGURE 3.2. Schematic drawing of the experimental setup.

Prior to the first test session, subjects participated in an orientation session to become familiar with the handle/beam apparatus and to ensure that they were able to accomplish the experimental tasks. During the first of two test sessions, subjects performed torque production tasks. Four different masses (0.5 kg, 1.0 kg, 1.5 kg, and 2.0 kg) were suspended from the beam at different positions with respect to the handle in order to exert torques of 0 Nm, 0.375 Nm, 0.75 Nm, 1.125 Nm, and 1.5 Nm on the handle/beam apparatus in both clockwise (CW) and counterclockwise (CCW) directions (Table 3.1). According to the coordinate system used in this experiment, a CW torque resulted in supination of the hand and wrist, requiring a counterbalancing pronation torque to maintain the handle in an upright position. Likewise, a CCW torque caused pronation of the hand and wrist, necessitating a counterbalancing supination torque to keep the handle in a vertical orientation. There were 36 conditions in all; both CW and CCW rotations were exerted on the handle/beam apparatus in 16 trials (four loads $\times$ four torques), while zero external torque conditions were present in four trials (four loads). The conditions were presented in a balanced order.

At the beginning of each trial, subjects were instructed to grasp the handle, which was oriented vertically. A prismatic precision grip was utilized in this study, i.e., a grip configuration in which the tips of the fingers and thumb oppose each other (Cutkosky and Howe, 1990). When subjects indicated their readiness, a load was suspended from the beam. Subjects were instructed to use the minimal force necessary to stabilize the handle in a vertical position, while at the same time preventing the handle from slipping in the vertical direction. Subjects were not directed to use any particular combination of finger forces in order to achieve these goals. Once the subjects verbally expressed that they

TABLE 3.1. Positions of the four different masses with respect to the axis of rotation of the handle/beam apparatus in order to produce the different torque magnitudes. According to the coordinate system used in this experiment, positive (CCW) and negative (CW) external torques required counterbalancing supination and pronation moments, respectively.

Torque (Nm)	Mass (kg)	Distance (cm)
0	0.5	0
	1.0	0
	1.5	0
	2.0	0
± 0.375	0.5	± 7.6
	1.0	± 3.8
	1.5	± 2.6
	2.0	± 1.9
± 0.75	0.5	± 15.3
	1.0	± 7.6
	1.5	± 5.1
	2.0	± 3.8
± 1.125	0.5	± 22.9
	1.0	± 11.5
	1.5	± 7.6
	2.0	± 5.7
± 1.5	0.5	± 30.6
	1.0	± 15.3
	1.5	± 10.2
	2.0	± 7.6

were using the minimal force necessary to stabilize the handle, the trial was ended. The force values of the individual fingers were recorded at the instant when the smallest total force was produced. Typically, subjects required 2-3 s to produce the torque necessary to return the handle to the vertical position and an additional 7-10 s to reach the minimal

total force. For all trials, the finger and thumb force data were collected at 100 Hz and filtered using a fourth-order low-pass Butterworth filter with a cutoff frequency of 5 Hz. Note that in this experiment, static tasks were studied and small fluctuations of the finger forces were not an object of analysis. A two- to three-minute break was given after each trial to avoid fatigue.

During the second test session, subjects performed maximal four-finger and individual finger force tasks. These trials utilized the same handle/beam apparatus as used in the torque production tasks. However, the handle was fixed to prevent rotation. In the maximal four-finger force task, subjects were asked to produce as large a force as possible using the index, middle, ring, and little fingers simultaneously; subjects were not directed to use any particular combination of finger forces to achieve this goal. The force values of the individual fingers were recorded at the instant when the largest total force was produced by all four fingers in combination. Subjects were given two attempts at this task; the maximal force values for each finger were averaged across the two attempts. In the maximal individual finger force task, subjects were asked to produce as large a force as possible using the index, middle, ring, or little finger by itself. The force value for a given finger was recorded at the instant when the largest force was produced by that finger. Subjects were given two attempts at this task for each finger; the maximal force value for a given finger was averaged across the two attempts for that finger. Typically, subjects required 2-5 s to produce maximal finger forces.

In addition, an estimation of the coefficient of static friction between the skin of the fingertips and the sandpaper covering the grasping surfaces of the handle was performed. During a series of ten trials with external loads of 0 kg, 0.5 kg, 1.0 kg, 1.5 kg,

and 2.0 kg (two trials with each load) and a torque of 0 Nm, the subjects were instructed to grip the handle and then slowly decrease their grasp force until a linear slip occurred. The onset of linear slip was determined by a sudden decrease in tangential force measured at the thumb. The ratio between the normal force and tangential force at slip (*slip ratio*) was determined (Johansson and Westling, 1984; Westling and Johansson, 1984); the inverse of the slip ratio was used as an estimate of μ. The coefficient of static friction μ was calculated across all subjects to be 1.72 ± 0.44.

3.4. DESIGN AND ANALYSIS

The following parameters were calculated:

1. *Total finger normal force*. The total normal force (F_{tot}) is the sum of the normal forces produced by the individual fingers.

$$F_{tot} = \sum_{i=1}^{4} F_i \qquad i = I, M, R, L \tag{3.1}$$

2. *Slip force*. The slip force (F_{slip}) is the minimal value of F_{tot} required to stop the object from slipping.

$$F_{slip} = F_{threshold} / \mu \tag{3.2}$$

where $F_{threshold}$ is the minimal shear force that prevents slipping and μ is the coefficient of static friction.

3. *Safety margin*. The normal force safety margin (F_{safe}) is the difference between the total normal finger force (F_{tot}) and the slip force (F_{slip}) computed for each trial.

$$F_{safe} = F_{tot} - F_{slip} \tag{3.3}$$

4. *Force sharing*. Force sharing (S_i) of an individual finger i is defined as the percentage of the normal force produced by that finger relative to the total normal

force F_{tot}. Note that the sum of the individual finger force sharing values involved in a task always equals 100%.

$$S_i = F_i / F_{tot} \times 100\% \qquad i = I, M, R, L \qquad (3.4)$$

5. *Force actualization*. Force actualization (A_i) of an individual finger *i* is defined as the percentage of the normal force produced relative to the maximal normal force produced by that finger in either single-finger ($A_{i/i}$) or four-finger tasks ($A_{i/IMRL}$).

$$A_{i/i} = F_i / F_{imax} \times 100\% \qquad i = I, M, R, L \qquad (3.5a)$$

$$A_{i/IMRL} = F_i / F_{IMRLmax} \times 100\% \qquad i = I, M, R, L \qquad (3.5b)$$

6. *Individual finger moment*. The moment (M_i) of an individual finger *i* is defined as the product of the normal force produced by that finger and the distance of the point of force application relative to the center of the thumb transducer.

$$M_i = F_i \times d_i \qquad i = I, M, R, L \qquad (3.6)$$

As previously noted (see Section 1.4), calculations of M_i may be affected by possible displacements of the digit/force transducer contact points during prehension tasks.

6. *Total moment*. The total moment (M_{tot}) is the sum of the moments produced by the individual fingers about the axis of rotation of the handle (the center of the thumb transducer of the handle/beam apparatus).

$$M_{tot} = \sum_{i=1}^{4} M_i \qquad i = I, M, R, L \qquad (3.7)$$

8. *Neutral line*. The position of the neutral line (*D*) is the moment arm of the total force produced by all four fingers in combination, i.e., the distance from the point of application of the resultant force to the axis of rotation of the ‘inverted-T’ handle (the center of the thumb transducer). It is an imaginary line parallel to the longitudinal

axis of the hand with respect to which the sum of the four moments produced by individual finger forces is zero.

$$D = \frac{\sum F_i \times d_i}{\sum F_i} \qquad i = I, M, R, L \qquad (3.8)$$

9. *Agonist moment*. The agonist moment (M_{ag}) is the sum of the moments produced by the agonist pair of fingers (the index and middle fingers for tasks requiring pronation moments and the ring and little fingers for tasks requiring supination moments) in the intended direction of the total moment.

$$M_{ag} = \sum_{i=1}^{2} M_i \qquad i = I \text{ and } M \text{ (Pro), or } R \text{ and } L \text{ (Sup)} \qquad (3.9)$$

10. *Antagonist moment*. The antagonist moment (M_{ant}) is the sum of the moments produced by the antagonist pair of fingers (the index and middle fingers for tasks requiring supination moments and the ring and little fingers for tasks requiring pronation moments) in the opposite direction of the total moment.

$$M_{ant} = \sum_{i=1}^{2} M_i \qquad i = I \text{ and } M \text{ (Sup), or } R \text{ and } L \text{ (Pro)} \qquad (3.10)$$

For trials in which the combined behavior of all four fingers was of primary interest, data were analyzed using a repeated measures analysis of variance (ANOVA) with two within subjects factors, load (0.5, 1.0, 1.5, and 2.0 kg) and torque (0, +/- 0.375, +/- 0.75, +/- 1.125, and +/- 1.5 Nm). For trials in which the behavior of individual fingers was of primary interest, a multivariate ANOVA (MANOVA) with repeated measures was used to analyze the data using Wilks' lambda. Post-hoc analyses were performed to identify differences between means using the Newman-Keuls method. Significance was determined at the .05 level.

CHAPTER 4

RESULTS

This chapter will present experimental results that addresses the issue of forces exerted by five digits on a hand-held object during static force and torque production tasks. The chapter consists of two parts: the first section will present biomechanical data, and the second section will analyze torque control using optimization techniques and a neural network approach developed previously to analyze multi-finger force production tasks (Zatsiorsky *et al*., 1998). In particular, the network is used to reconstruct the neural commands sent to individual fingers.

In this experiment, the term *moment* is used for designating the moment of force produced by a finger force(s) about an axis of rotation located at the center of the thumb transducer. The term *external torque* is used for designating the moment of force generated by the external load. The term *torque* refers to the total torque exerted on the handle by the subject; it is equal in magnitude but opposite in direction to the external torque. Only the normal forces (perpendicular to the handle) produced by the fingers were measured. For the thumb, both the normal and shear forces were recorded.

4.1. BIOMECHANICS OF FORCE AND TORQUE PRODUCTION

4.1.1. THUMB FORCES

The thumb normal force changed systematically with the external load and torque (Figure 4.1). Analysis of the thumb normal force indicated significant main effects for load, $F(3, 51) = 139.50$, $p < 0.0001$, and torque, $F(8, 136) = 177.47$, $p < 0.0001$. The

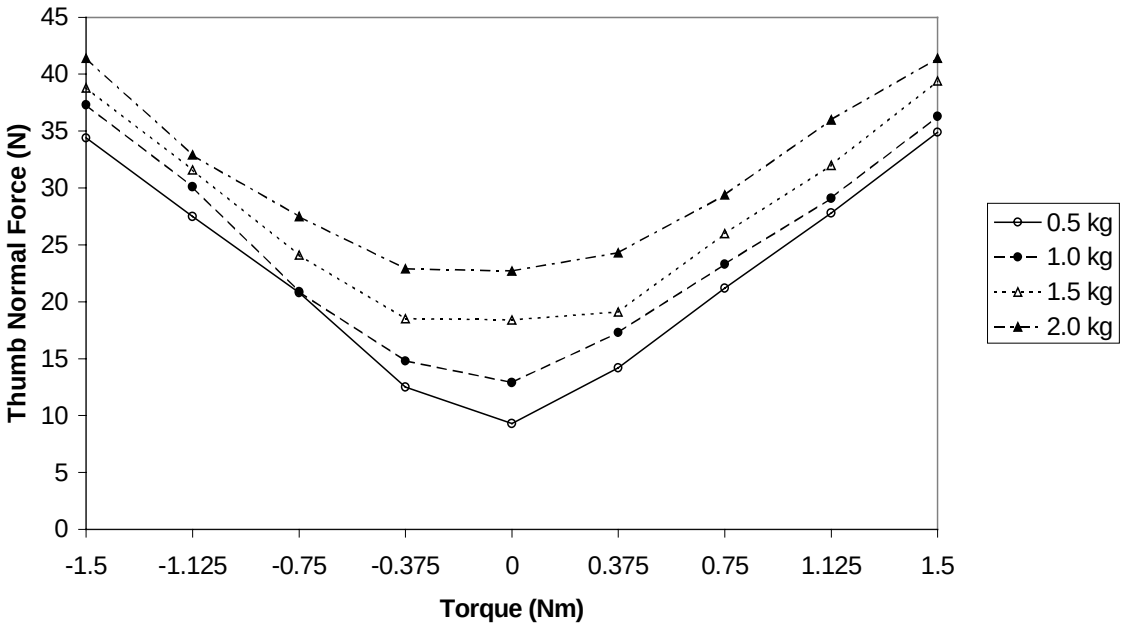


FIGURE 4.1. Thumb normal force (N) as a function of external load and torque. Positive (CCW) and negative (CW) external torques correspond to counterbalancing supination and pronation moments, respectively. In this and subsequent figures the data represent the group average.

interaction effect between load and torque was also significant, $F(24, 408) = 2.61$, $p < 0.0001$. The thumb normal force ranged from approximately 9-23 N in the zero torque conditions to 34-41 N in the ± 1.5 Nm torque conditions; standard deviations varied from 3.3-8.1 N. Post-hoc analysis revealed that the thumb normal force increased significantly with increases in both load and torque magnitude. The magnitude of the thumb normal force did not depend on the direction of the external torque.

The thumb shear force also changed systematically with the external load and torque (Figure 4.2). Analysis of the thumb shear force indicated significant main effects for load, $F(3, 51) = 349.55$, $p < 0.0001$, and torque, $F(8, 136) = 162.37$, $p < 0.0001$. The thumb shear force ranged from approximately 3-8 N in the –1.5 Nm conditions to 13-19 N in the 1.5 Nm conditions; standard deviations varied from 0.8-4.3 N. Post-hoc

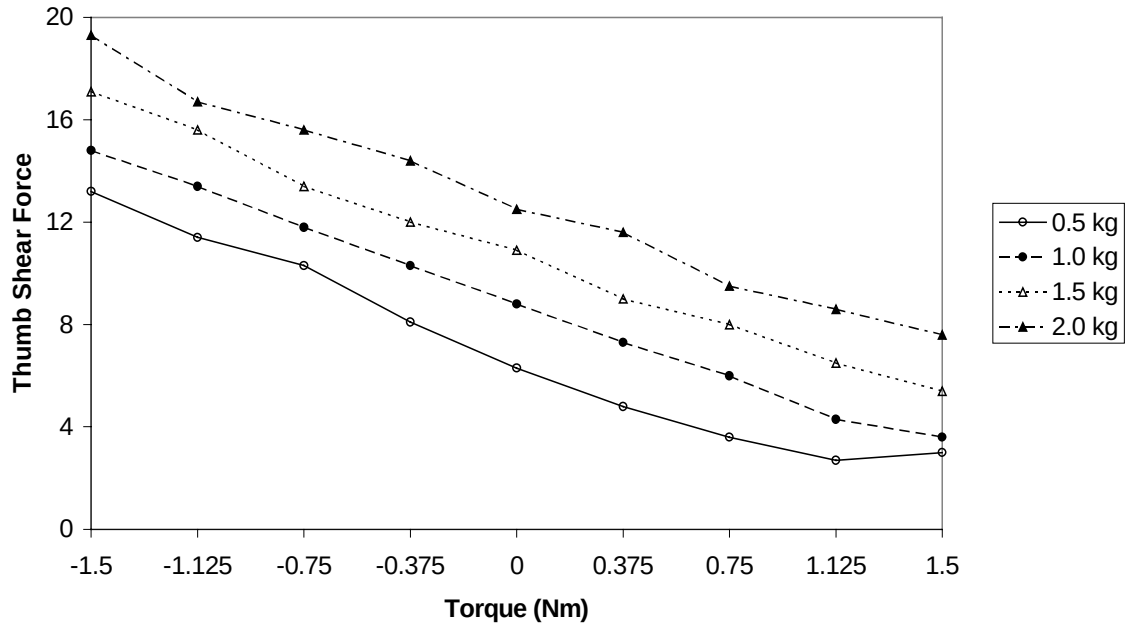


FIGURE 4.2. Thumb shear force (N) as a function of external load and torque.

analysis revealed that the thumb shear force increased significantly with increases in load. In addition, shear force increased during supination efforts and decreased during pronation efforts. In the subsequent description of the results, analysis will be limited to the forces produced by the fingers.

4.1.2. TORQUE PRODUCTION

The total moment M_{tot} generated by the normal forces of the four fingers is presented in Figure 4.3. Analysis of M_{tot} indicated a significant main effect for torque, $F(4, 68) = 673.12$, $p < 0.0001$. The magnitude of M_{tot} was approximately one-half of the external torque. Post-hoc analysis revealed that M_{tot} increased significantly with increases in torque; however, the relationship did not depend on the external load. The relationship between M_{tot} and torque was evidently linear ($r = 0.98$-0.99). The coefficients of the regression equation $Moment = a(Torque) + b$ are: intercept $a = 0.06$,

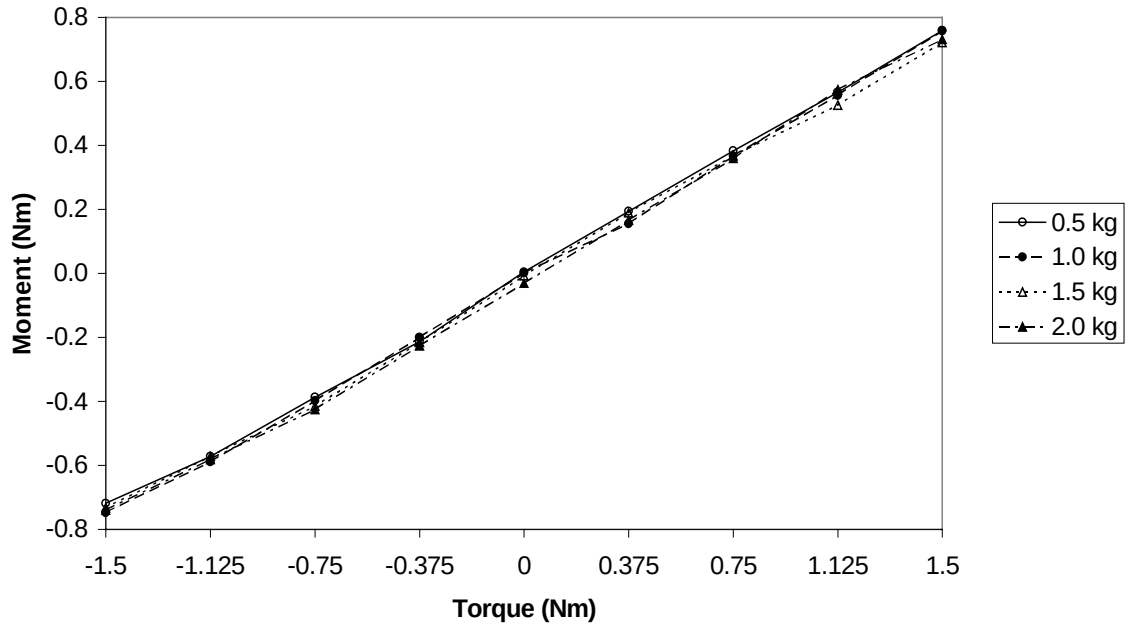


FIGURE 4.3. Relationship between the torque that counterbalances the external load and the moment produced by the normal forces of the fingers.

0.02, -0.01, and –0.01 and slope b = 0.451, 0.473, 0.492, and 0.504 for the 0.5 kg, 1.0 kg, 1.5 kg, and 2.0 kg loads, respectively. Because the magnitude of M_{tot} was approximately one-half of the external torque, the other half of the counterbalancing torque was produced by the shear forces of the fingers and thumb.

The total moment M_{tot} produced by the normal forces of the four fingers about the axis of rotation located at the center of the thumb transducer is equal to the sum of the moments generated by the individual fingers about this pivot point:

$$M_{tot} = \sum M_i = \sum F_i d_i = [F_i]^T [d_i] = F_{tot} [S_i]^T [d_i] = F_{tot} D \tag{4.1}$$

where $[F_i]^T$ is the transpose of the vector of finger forces, $[d_i]$ is the vector of the finger moment arms, $[S_i]^T$ is the transpose of the vector of force sharing values (percentage of the total force), and $D = [S_i]^T[d_i]$ is the moment arm of the resultant force with respect to the axis of rotation; D represents the location of the resultant of the normal forces of the

four fingers (also referred to as the neutral line). Changes in M_{tot} can be due to variations in F_{tot} and/or in $D = [S_i]^T[d_i]$. Because $[d_i]$ is constant, changes in $[S_i]$ are the real source of variation in D.

4.1.3. TOTAL FINGER FORCES

The total force F_{tot} i.e., the sum of the normal forces exerted on the handle by the individual fingers, is presented in Figure 4.4. Analysis of F_{tot} indicated significant main effects for load, $F(3, 51) = 139.50$, $p < 0.0001$, and torque, $F(8, 136) = 177.47$, $p < 0.0001$. The interaction effect between load and torque was also significant, $F(24, 408) = 2.61$, $p < 0.0001$. Note that F_{tot} was equal to the normal force of the thumb (see Figure 4.1). During a static task, the sum of all the normal forces acting on the handle must equal zero; therefore, F_{tot} was equal in magnitude to the normal thumb force. The relationship between F_{tot} and torque can be modeled using the second-order polynomial $F_{tot} = a(Torque)^2 + b(Torque) + c$ (based on least squares curve fitting); the coefficients

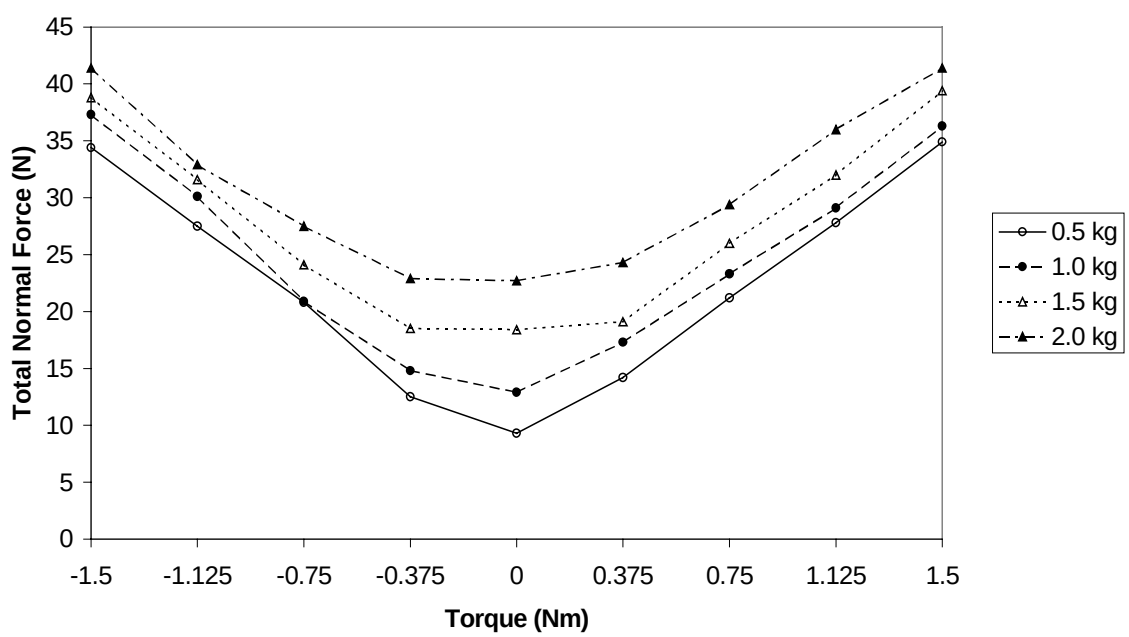


FIGURE 4.4. Total normal force F_{tot} (N) as a function of external load and torque.

are a = 10.387, 10.141, 9.4433, and 8.3982, b = 0.2485, 0.0034, 0.3335, and 0.638, and c = 12.771, 15.163, 18.69, and 23.081 for the 0.5 kg, 1.0 kg, 1.5 kg, and 2.0 kg load conditions, respectively. The total force F_{tot} ranged from approximately 9-23 N in the zero torque conditions to 34-41 N in the ± 1.5 Nm torque conditions; standard deviations varied from 3.3-8.1 N. Post-hoc analysis revealed that F_{tot} increased significantly with increases in both load and torque magnitude. The magnitude of F_{tot} did not depend on the direction of the external torque. These findings are in agreement with previous studies that examined the control of index finger-thumb precision grip when holding objects that were subjected to torque loads (Goodwin *et al*. 1998, Johansson *et al*. 1999, Kinoshita *et al*. 1997).

The risk of slipping during the tasks studied was not an issue since the slip force F_{slip}, the minimal grasp force that is necessary to prevent an object from slipping out of the hand, was much smaller than F_{tot}. The slip force F_{slip}, at zero torque was computed as 0.5[(*External Load* + 1.0 kg)/μ], where μ is the coefficient of static friction (μ = 1.72); F_{slip} was equal to 4.27 N, 5.70 N, 7.12 N, and 8.55 N for the 0.5 kg, 1.0 kg, 1.5 kg, and 2.0 kg loads, respectively. Note the large safety margins F_{safe} (Figure 4.5). The safety margin F_{safe} is the grip force applied to an object in excess of that required to oppose the load force and prevent the object from slipping. Analysis of F_{safe} indicated significant main effects for load, $F(3, 51) = 19.39$, $p < 0.0001$, and torque, $F(8, 136) = 230.44$, $p < 0.0001$. In addition, the interaction between load and torque was also significant, $F(24, 408) = 3.11$, $p < 0.0001$. The safety margin F_{safe} ranged from approximately 5-13 N in the zero torque conditions to 27-36 N in the ± 1.5 Nm torque conditions; standard deviations varied from 3.3-7.1 N. Post-hoc analysis revealed that F_{safe} increased

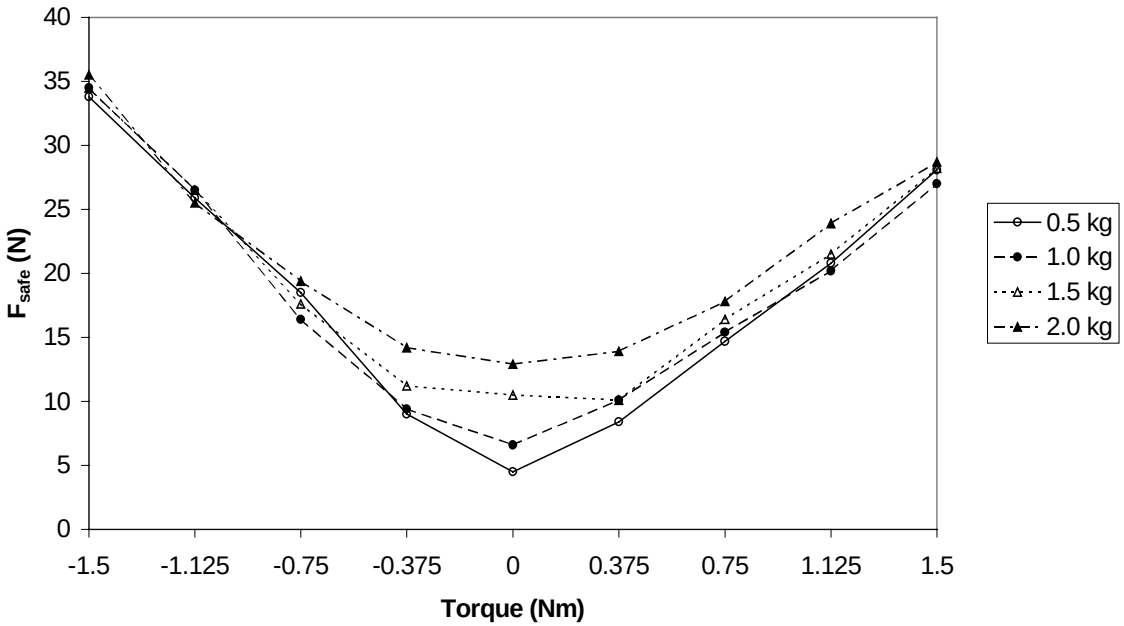


FIGURE 4.5. Absolute safety margin F_{safe} (N) as a function of the external load and torque.

significantly with increases in both load and torque magnitude. The magnitude of F_{safe} (approximately 50-100% of the grip force) is much larger than previously reported when an object held by a precision grip between the thumb and index finger is subjected to rotation (generally some 20-40% of the grip force; Goodwin *et al*. 1998, Johansson *et al*. 1999, Kinoshita *et al*. 1997).

The moment arm of the total force *D*, i.e., the distance from the point of application of the resultant force to the axis of rotation located at the center of the thumb transducer, changed sharply when the external torque increased in magnitude from 0 Nm to 0.375 Nm, but further increases in the external torque caused smaller displacements in the point of force application (Figure 4.6). The larger external torques (1.125 Nm and 1.5 Nm) were counterbalanced primarily by increases in the magnitude of F_{tot}, while the moment arm of the resultant force changed only slightly (especially for CW external

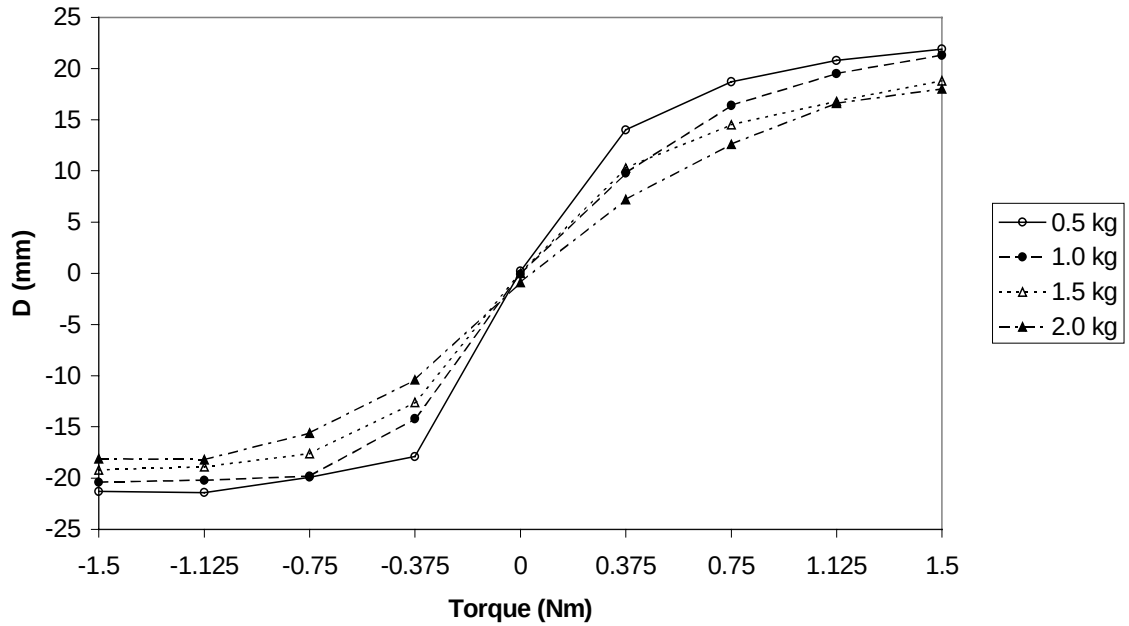


FIGURE 4.6. Position of the point of application *D* (mm) of the total normal finger force F_{tot} as a function of external load and torque.

torques/pronation moments). Therefore, depending on the magnitude of the external torque, subjects used different strategies to counterbalance the external torque. From Figures 4.4 and 4.6 and Eq. 4.1, it follows that small external torques are controlled mainly by changes in the force sharing pattern (i.e., the redistribution of forces among the fingers), while large external torques are primarily controlled by the magnitude of F_{tot}. External torques of equal magnitudes in the CW and CCW directions caused displacement of the point of force application by similar magnitudes.

The total shear force F_{shear}, i.e., the sum of the shear forces exerted on the handle by the individual fingers, is presented in Figure 4.7. Analysis of F_{shear} indicated significant main effects for load, $F(3, 51) = 852.77$, $p < 0.0001$, and torque, $F(8, 136) = 167.58$, $p < 0.0001$. The interaction effect between load and torque was also significant, $F(24, 408) = 1.77$, $p < 0.05$. The total shear force F_{shear} increased during pronation

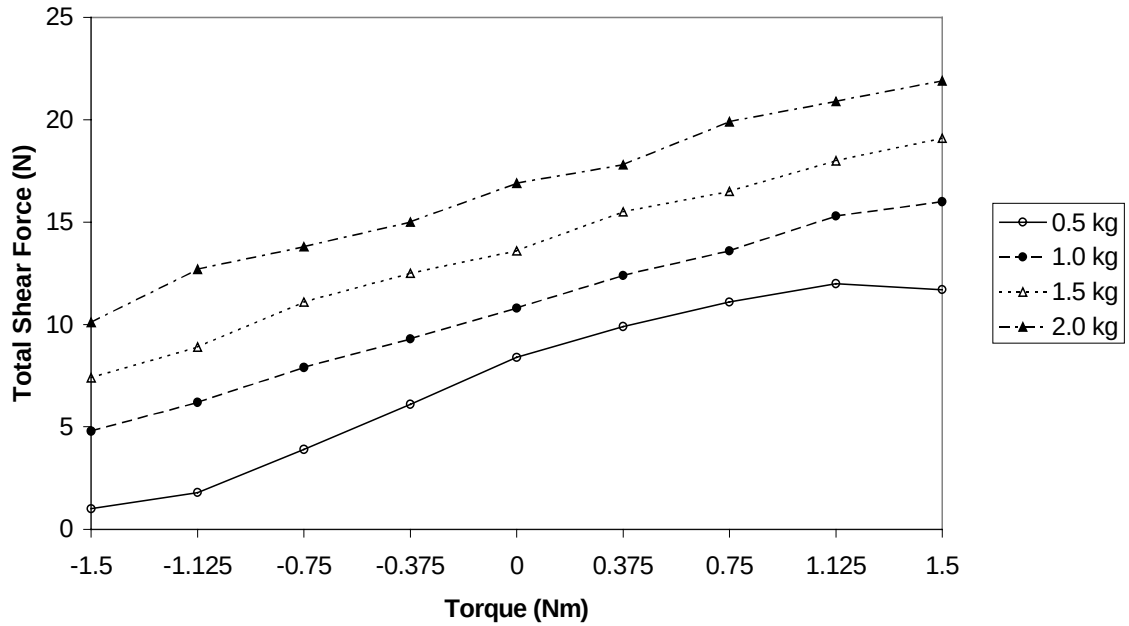


FIGURE 4.7. Total shear force F_{shear} (N) as a function of external load and torque.

efforts and decreased during supination efforts; F_{shear} ranged from approximately 1-10 N in the –1.5 Nm torque conditions to 12-22 N in the 1.5 Nm torque conditions; standard deviations varied from 0.8-4.3 N. Post-hoc analysis revealed that F_{shear} increased significantly with increases in both load and torque. Note that F_{shear} increased as thumb shear force decreased, and vice versa (see Figure 4.2); this demonstrates that the sum of the shear forces exerted by the fingers and thumb was equal to the total weight of the 'inverted-T' handle and external load.

4.1.4. Individual Finger Forces: Sharing Labor Among the Fingers

The forces produced by the individual fingers as a function of external torque are presented in Figure 4.8 (2.0 kg load condition; data for all load conditions and representative subject data are presented in Appendix B). Analysis of the individual finger normal forces indicated significant main effects for load, $F(4, 50) = 15.87$,

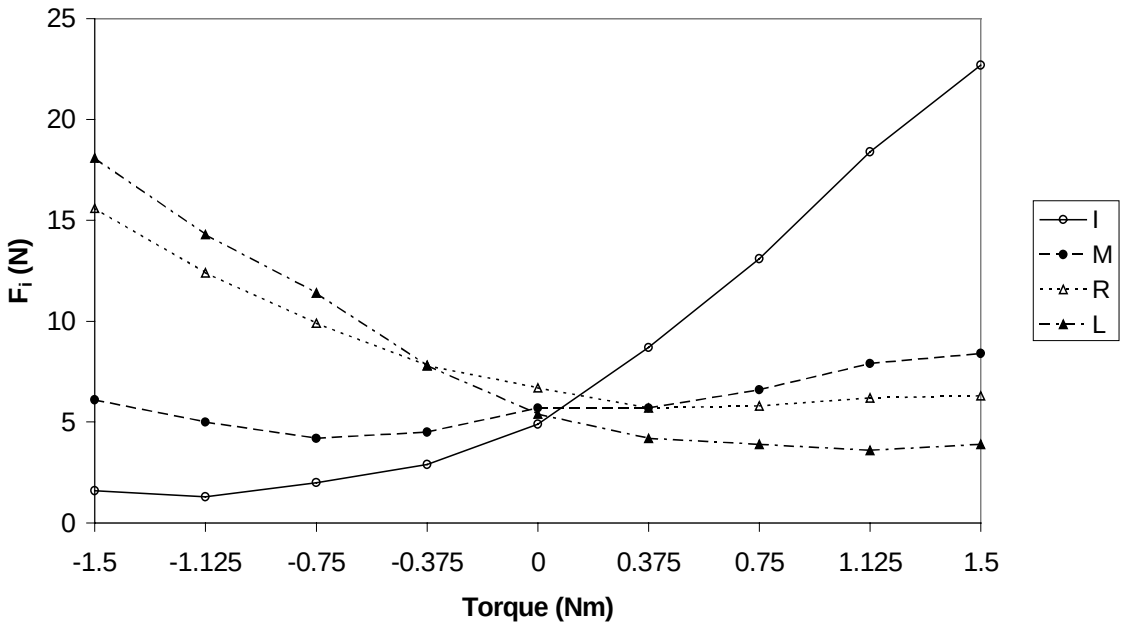


FIGURE 4.8. Individual finger normal forces F_i (N) for the 2.0 kg load condition as a function of external torque.

$p < 0.0001$, and torque, $F(8, 136) = 91.79$, $p < 0.0001$. In addition, the interaction effect between load and torque was also significant, $F(24, 408) = 1.36$, $p < 0.05$. Post-hoc analysis revealed that during pronation efforts, the largest forces were produced by the index finger, followed by the middle, ring, and little fingers in decreasing order; during supination efforts, the largest forces were generated by the ring, middle, and index fingers in decreasing order. When producing the largest pronation moment, the forces produced by the index, middle, ring, and little fingers ranged from 21.5-22.7 N, 6.3-8.4 N, 3.3-6.3 N, and 2.3-3.9 N, respectively, for the four load conditions. During the production of the largest supination moment, the forces produced by the index, middle, ring, and little fingers ranged from 0.8-1.6 N, 3.5-6.1 N, 13.5-15.6 N, and 16.6-18.1 N, respectively, for the four load conditions. The standard deviations for the index, middle, ring, and little finger forces F_i varied from 0.7-3.7 N, 0.6-3.1 N, 1.1-6.0 N, and 1.1-3.7 N, respectively.

In addition, post-hoc analysis indicated that the individual finger forces increased significantly with increases in load for all four fingers. Also, all four fingers produced significantly greater forces with increases in torque when working as agonists. When functioning as antagonists, the forces generated by the index, ring, and little fingers did not change as a function of torque; the middle finger exerted significantly greater force with increases in torque from 0.75-1.5 Nm.

The forces produced by the 'peripheral' (index and little) fingers depended mainly on the external torque to be counterbalanced while the forces generated by the 'central' (middle and ring) fingers depended on both the external load and torque. Hence, the peripheral fingers were the main moment generators. When the index finger was working as an agonist, it exerted a force that was proportional to the pronation moment; this relationship was found to be linear. When a supination moment was required, the index finger was still active and generated an antagonist moment in a pronation direction. Likewise, the ring and little fingers contributed to the supination moment when working as agonists and were not completely inactive when a pronation moment was required. The middle finger generated larger forces in response to larger external torques almost without regard to the direction of the external torque.

The force sharing values S_i exhibited by the individual fingers as a function of external torque are presented in Figure 4.9 (2.0 kg load condition; data for all load conditions and representative subject data are presented in Appendix C). Analysis of S_i indicated significant main effects for load, $F(4, 50) = 8.46$, $p < 0.0001$, and torque, $F(8, 136) = 34.98$, $p < 0.0001$. In addition, the interaction effect between load and torque was also significant, $F(24, 408) = 2.79$, $p < 0.0001$. Post-hoc analysis revealed that during

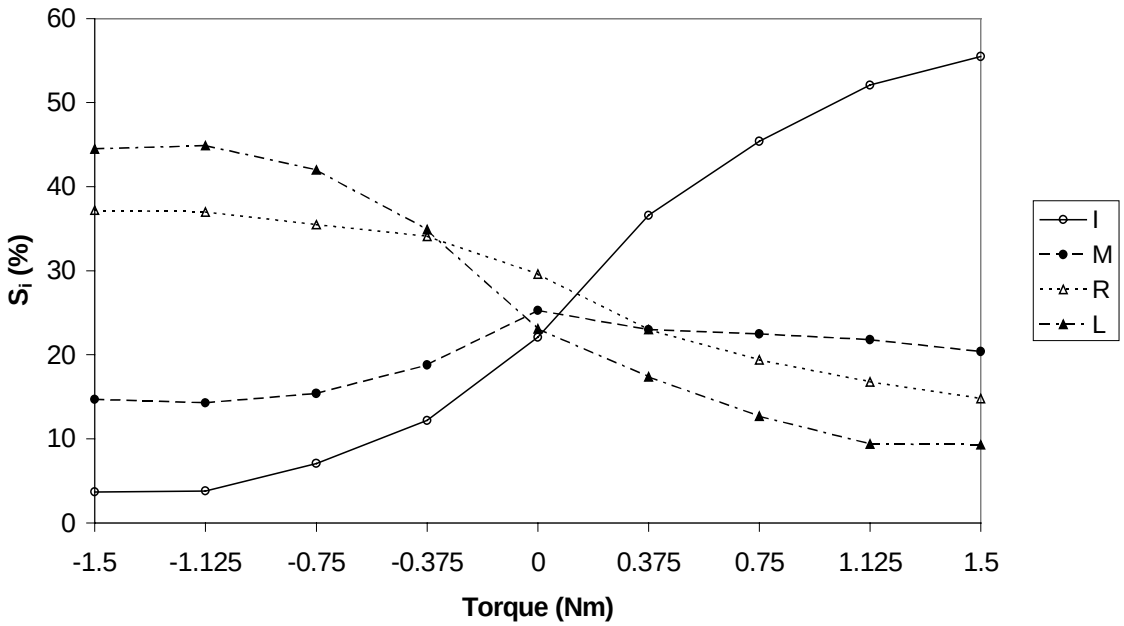


FIGURE 4.9. Individual finger force sharing values S_i (%) for the 2.0 kg load condition as a function of external torque.

pronation efforts, the largest and smallest S_i values were observed in the index and little fingers, respectively; the S_i values of the middle and ring fingers did not differ from each other and were intermediate to those of the index and little fingers. During supination efforts, the largest S_i values were observed in the little finger, followed by the ring, middle, and little fingers in decreasing order. When producing the largest pronation moment, the S_i values demonstrated by the index, middle, ring, and little fingers ranged from 55.5-64.0%, 18.1-22.1%, 9.5-14.8%, and 6.0-9.3%, respectively, for the four load conditions. During the production of the largest supination moment, the forces produced by the index, middle, ring, and little fingers ranged from 2.1-3.7%, 10.0-14.7%, 35.4-38.3%, and 44.5-49.6%, respectively, for the four load conditions. The standard deviations for the index, middle, ring, and little finger force sharing values S_i varied from 1.9-9.7%, 3.6-8.0%, 3.1-9.7%, and 3.8-10.7%, respectively. In addition, post-hoc

analysis indicated that the force sharing values decreased significantly with increases in load for the index and little fingers, while they increased significantly with increases in load for the middle and ring fingers. The four fingers displayed varying force sharing patterns when working as agonists. The force sharing percentage exhibited by the index finger increased significantly with increases in torque, while the values exhibited by the ring and little fingers increased as the torque increased from 0-0.75 Nm but remained constant with further increases in torque. The force sharing values of the middle finger did not change when it functioned as an agonist.

4.1.5. Individual Finger Forces: Force Actualization

The maximal normal forces produced by individual fingers in single-finger and four-finger maximal voluntary force production tasks are presented in Table 4.1. A simple ANOVA was used to assess the differences in maximal force production by individual fingers within the two tasks. In the single-finger task, the index finger produced significantly greater force than the middle finger, which generated greater force than the ring and little fingers; there were no differences in the forces produced by the ring and little fingers, $F(3, 51) = 67.57$, $p < 0.0001$. In the four-finger task, the forces produced by the index, middle, and ring fingers were not different; however, these three fingers generated significantly larger forces than the little finger, $F(3, 51) = 83.20$, $p < 0.0001$. Dependent *t* tests were used to assess the differences in maximal force production by the individual fingers between the single-finger and four-finger tasks. The maximal forces generated by the index ($t(17) = 9.15$, $p < 0.0001$), middle ($t(17) = 4.33$, $p < 0.0005$), ring ($t(17) = 3.53$, $p < 0.005$), and little ($t(17) = 7.12$, $p < 0.0001$) were larger in the single-finger task. The maximal forces produced by the index, middle, ring, and

TABLE 4.1. Maximum individual finger forces (N) produced in single-finger and four-finger tasks. The letters I, M, R, and L stand for the index, middle, ring, and little fingers, respectively.

Task		I	M	R	L
Single-finger	Mean	73.0	42.4	34.3	28.1
	St. Dev.	23.1	12.8	9.5	8.5
Four-finger	Mean	30.7	33.2	28.8	18.5
	St. Dev.	8.0	12.0	9.5	5.2

little fingers decreased 57.9, 21.7, 16.0, and 34.2%, respectively, in the four-finger tasks as compared to the single-finger tasks. The sum of the maximal forces produced by all four fingers individually was 177.8 N, which exceeded the maximal force of 111.2 N generated by all four fingers simultaneously by 37.5%.

The force actualization values $A_{i/i}$ demonstrated by individual fingers relative to the maximal forces in single-finger tasks as a function of external torque are presented in Figure 4.10 (2.0 kg load condition; data for all load conditions and representative subject data are presented in Appendix D). Analysis of $A_{i/i}$ indicated significant main effects for load, $F(4, 50) = 11.33$, $p < 0.0001$, and torque, $F(8, 136) = 41.61$, $p < 0.0001$. The interaction effect between load and torque was also significant, $F(24, 408) = 1.48$, $p < 0.005$. Post-hoc analysis revealed that during pronation efforts, the largest $A_{i/i}$ values were demonstrated by the index finger; there was no difference in $A_{i/i}$ values between the middle, ring, and little fingers; during supination efforts, the largest $A_{i/i}$ values were found in the little finger, followed by the ring, middle, and index fingers in decreasing order. When producing the largest pronation moment, the $A_{i/i}$ values demonstrated by the index,

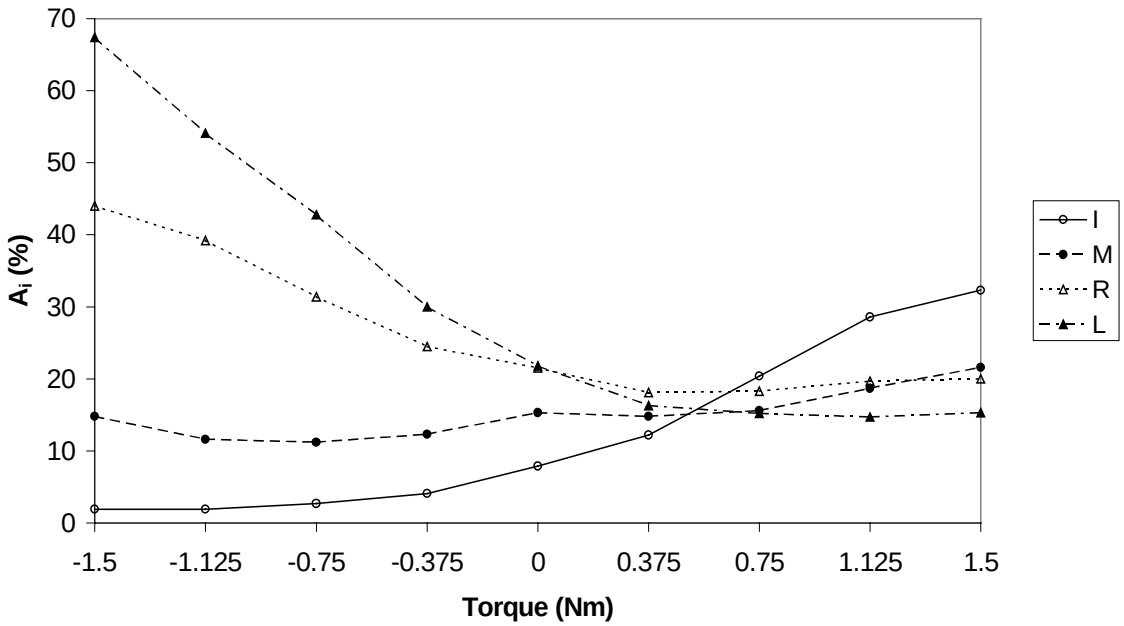


FIGURE 4.10. Individual finger force actualization values $A_{i/i}$ (%) relative to maximal forces produced in single-finger tasks for the 2.0 kg load condition as a function of external torque.

middle, ring, and little fingers ranged from 32.3-39.1%, 16.5-21.6%, 10.7-20.0%, and 9.0-15.3%, respectively, for the four load conditions. During the production of the largest supination moment, the $A_{i/i}$ values produced by the index, middle, ring, and little fingers ranged from 1.0-1.9%, 9.2-15.1%, 39.2-46.0%, and 61.7-67.4%, respectively, for the four load conditions. The standard deviations for the index, middle, ring, and little finger force actualization values $A_{i/i}$ varied from 0.9-15.3%, 2.9-11.2%, 4.7-19.7%, and 3.2-19.0%, respectively. The larger $A_{i/i}$ values demonstrated by the ring and little fingers as compared to the index and middle fingers are evidently due to the smaller maximal strength values of the ring and little fingers. In addition, post-hoc analysis indicated that $A_{i/I}$ values increased significantly with increases in load for the middle, ring, and little fingers; the index finger demonstrated its largest $A_{i/i}$ values in the 2.0 kg load condition, while there were no differences in $A_{i/i}$ between the 0.5 kg, 1.0 kg, and 1.5 kg load

conditions. Also, all four fingers produced significantly greater $A_{i/i}$ values with increases in torque when working as agonists. When functioning as antagonists, the $A_{i/i}$ values generated by the index, ring, and little fingers did not change as a function of torque; the middle finger demonstrated significantly larger $A_{i/i}$ values in the 1.5 Nm torque condition compared to the 0.375 Nm, 0.75 Nm, and 1.125 Nm torque conditions.

The force actualization values $A_{i/IMRL}$ demonstrated by individual fingers relative to the maximal forces in a four-finger task as a function of external torque are presented in Figure 4.11 (2.0 kg load condition; data for all load conditions and representative subject data are presented in Appendix E). Analysis of $A_{i/IMRL}$ indicated significant main effects for load, $F(4, 50) = 13.20$, $p < 0.0001$, and torque, $F(8, 136) = 43.61$, $p < 0.0001$. The interaction effect between load and torque was also significant, $F(24, 408) = 1.41$, $p < 0.01$. Post-hoc analysis revealed that during pronation efforts, the largest $A_{i/IMRL}$ values

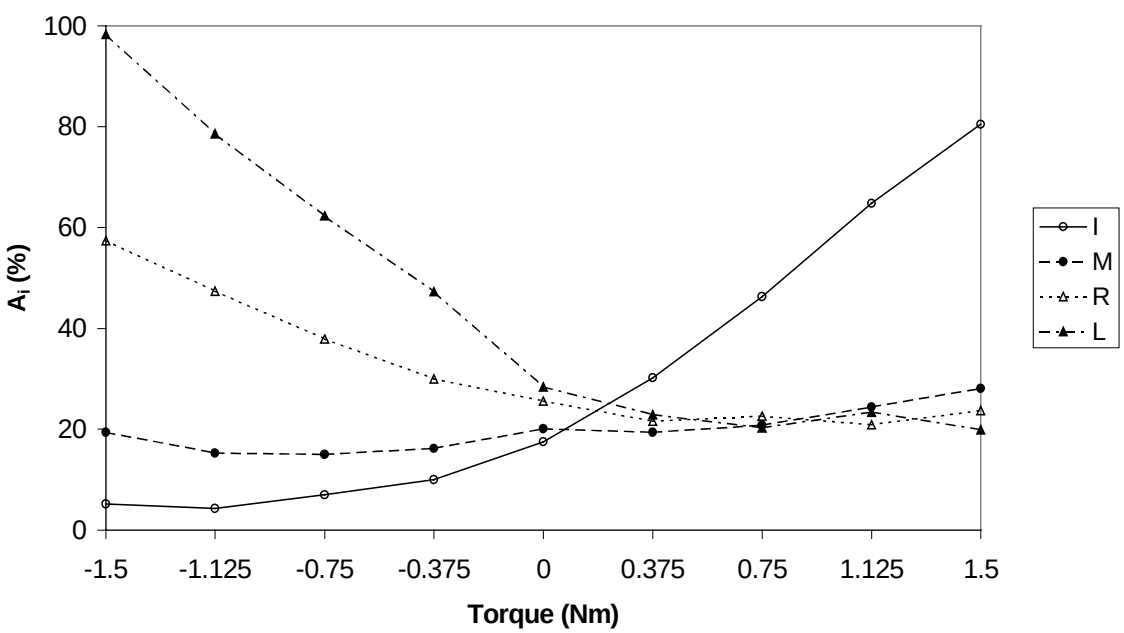


FIGURE 4.11. Individual finger force actualization values $A_{i/IMRL}$ (%) relative to maximal forces produced in a four-finger task for the 2.0 kg load condition as a function of external torque.

were demonstrated by the index finger; there was no difference in $A_{i/IMRL}$ values between the middle, ring, and little fingers in decreasing order. During supination efforts, the largest $A_{i/IMRL}$ values were found in the little finger, followed by the ring, middle, and index fingers in decreasing order. When producing the largest pronation moment, the $A_{i/IMRL}$ values demonstrated by the index, middle, ring, and little fingers ranged from 75.5-80.5%, 21.4-28.1%, 12.5-23.7%, and 12.3-19.9%, respectively, for the four load conditions. During the production of the largest supination moment, the forces produced by the index, middle, ring, and little fingers ranged from 2.6-5.2%, 12.4-19.4%, 50.0-57.4%, and 97.1-101.5%, respectively, for the four load conditions. The standard deviations for the index, middle, ring, and little finger force actualization values $A_{i/IMRL}$ varied from 2.3-30.2%, 4.0-13.2%, 4.2-22.6%, and 5.8-33.8%, respectively. The larger $A_{i/IMRL}$ values demonstrated by the ring and little fingers as compared to the index and middle fingers are evidently due to the smaller maximal strength values of the ring and little fingers. In addition, post-hoc analysis indicated that $A_{i/IMRL}$ values increased significantly with increases in load for the middle, ring, and little fingers; the index finger demonstrated its largest $A_{i/IMRL}$ values in the 2.0 kg load condition followed by the 1.5 kg load condition, while there were no differences in $A_{i/IMRL}$ between the 0.5 kg and 1.0 kg load conditions. Also, all four fingers produced significantly greater $A_{i/IMRL}$ values with increases in torque when working as agonists. When functioning as antagonists, the $A_{i/IMRL}$ values generated by the index, ring, and little fingers did not change as a function of torque; the middle finger demonstrated significantly larger $A_{i/IMRL}$ values in the 1.5 Nm torque condition compared to the 0.375 Nm, 0.75 Nm, and 1.125 Nm torque conditions.

4.1.6. INDIVIDUAL FINGER MOMENTS: AGONIST AND ANTAGONIST MOMENTS

The individual fingers exerted moments of force M_i in the intended direction of the total moment (*agonist moments*; M_{ag}) as well as in the opposite direction (*antagonist moments*; M_{ant}). For example, the index and middle fingers produced force in tasks requiring pronation moments. However, the ring and little fingers were not inactive; they generated force and produced supination (antagonist) moments. The moments produced by the individual fingers about the axis of rotation of the 'inverted-T' handle located at the center of the thumb transducer are presented in Figure 4.12 (2.0 kg load condition; data for all load conditions and representative subject data are presented in Appendix E). Analysis of individual finger moments indicated significant main effects for load, $F(4, 50) = 14.16$, $p < 0.0001$, and torque, $F(8, 136) = 116.19$, $p < 0.0001$. The interaction effect between load and torque was also significant, $F(24, 408) = 3.90$, $p < 0.0001$. Post-hoc analysis indicated that during pronation efforts, the index finger produced larger M_{ag} than the middle finger and the

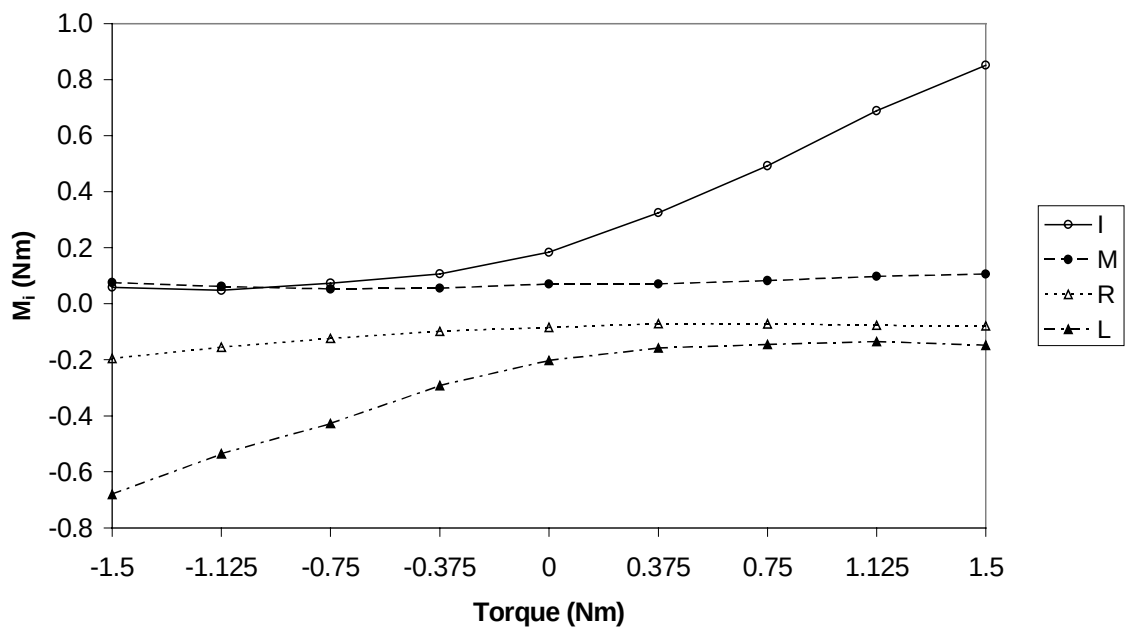


FIGURE 4.12. Individual finger moments M_i (Nm) for the 2.0 kg load condition as a function of external torque.

little finger produced larger M_{ant} than the ring finger. During supination efforts, the little finger produced larger M_{ag} than the ring finger and the index finger produced larger M_{ant} than the middle finger. When producing the largest pronation moment, M_{ag} values of the index and middle fingers ranged from 0.806-0.852 Nm and 0.079-0.108 Nm, respectively, and the M_{ant} values of the ring and little fingers ranged from 0.041-0.079 Nm and 0.087-0.148 Nm, respectively, for the four load conditions. During the production of the largest supination moment, M_{ag} values of the ring and little fingers ranged from 0.169-0.195 Nm and 0.622-0.680 Nm, respectively, and the M_{ant} values of the index and ring fingers ranged from 0.029-0.059 Nm and 0.044-0.076 Nm, respectively, for the four load conditions. The standard deviations for the index, middle, ring, and little finger moments M_i varied from 0.027-0.139 Nm, 0.007-0.039 Nm, 0.014-0.075 Nm, and 0.037-0.139 Nm, respectively. In addition, post-hoc analysis indicated that M_i increased significantly with increases in load for the middle, ring, and little fingers; the index finger demonstrated significant increases in M_i as the load increased from 1.0 to 2.0 kg. When generating M_{ag}, all four fingers produced significantly larger M_i with increases in torque. During the production of M_{ant}, M_i for the index, ring, and little fingers did not change as a function of torque; M_i exerted by the middle finger increased as the torque increased from 0.75 to 1.5 Nm.

The M_{ant}/M_{ag} ratios exhibited in the different experimental conditions are presented in Figure 4.13. The antagonist moments M_{ant} were as large as 40-60% of M_{ag} for small external torques moments, while they were approximately 10-20% of M_{ag} for large external torques. Hence, some fingers ‘work in the wrong direction’. As a result, the fingers that generate M_{ag} should exert larger compensatory forces.

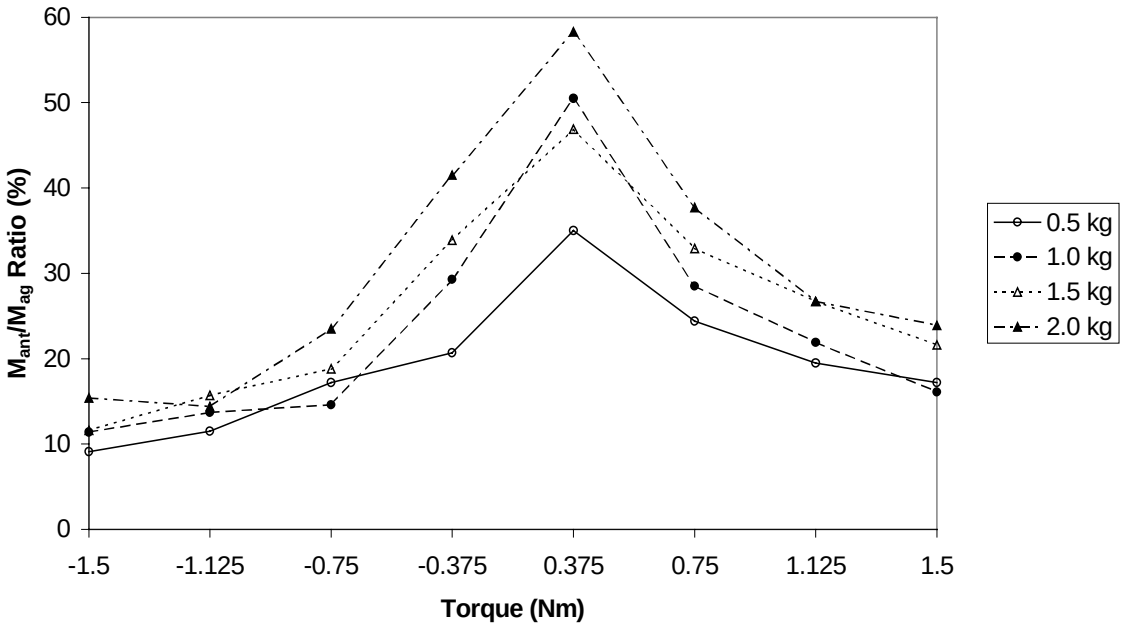


FIGURE 4.13. Antagonist/agonist moment ratio (%) as a function of external load and torque. Antagonist moments were observed over the entire range of load/toque combinations.

4.2. CONTROL OF FORCE AND TORQUE PRODUCTION

This section is based on the data reported in Section 4.1 and consists of three main parts: (1) optimization of finger forces, (2) reconstruction of neural commands, and (3) optimization of neural commands. Parts 2 and 3 are based on expanding a neural network approach previously developed for studying pressing tasks (Zatsiorsky *et al*., 1998) to precision grip tasks requiring simultaneous exertion of force and torque on a hand-held object.

4.2.1. OPTIMIZATION OF FINGER FORCES

The most widely used approach in modeling the force sharing problem is based on the assumption that the CNS optimizes a cost function during voluntary movement (for reviews, see Herzog, 1996; Prilutsky, 2000; Prilutsky and Zatsiorsky, 2002; Tsirakos

et al., 1997). Numerous cost functions have been introduced, but the majority provides a minimal norm solution (Kuo, 1994):

$$J = \left(\sum_{i=1}^{n} (x_i)^p \right)^{\frac{1}{p}} \rightarrow \min \tag{4.2}$$

where i is a given muscle that spans a joint, n is the total number of muscles spanning a joint, x_i is a performance variable (e.g., muscle force, force per unit of physiological cross-sectional area, force relative to a muscle's maximal force, force relative to a muscle's maximal moment), and p is the power of the objective function.

To test whether the observed force sharing patterns (see Section 4.1.4) were optimal, optimization techniques were employed. The norms of the following vectors were used as cost functions:

(1) Finger forces

$$J_1 = \left(\sum_{i=1}^{4} (F_i)^p \right)^{\frac{1}{p}} \rightarrow \min \tag{4.3}$$

(2) Finger forces normalized with respect to the maximal forces measured in single-finger tasks

$$J_2 = \left(\sum_{i=1}^{4} \left(\frac{F_i}{F_{mi}} \right)^p \right)^{\frac{1}{p}} \rightarrow \min \tag{4.4}$$

(3) Finger forces normalized with respect to the maximal forces measured in a four-finger task

$$J_3 = \left(\sum_{i=1}^{4} \left(\frac{F_i}{F_{IMRL}} \right)^p \right)^{\frac{1}{p}} \rightarrow \min \tag{4.5}$$

(4) Finger forces normalized with respect to the maximal moments measured in single-finger tasks

$$J_4 = \left(\sum_{i=1}^{4} \left(\frac{F_i}{M_{mi}} \right)^p \right)^{\frac{1}{p}} \rightarrow \min \tag{4.6}$$

(5) Finger forces normalized with respect to the maximal moments measured in a four-finger task

$$J_5 = \left(\sum_{i=1}^{4} \left(\frac{F_i}{M_{IMRL}} \right)^p \right)^{\frac{1}{p}} \rightarrow \min \tag{4.7}$$

using the following constraints:

$$F_{tot} > F_{slip};\ F_i \leq F_{imax};\ M_{tot} = \sum F_i d_i = constant \tag{4.8}$$

where F_{tot} is the total normal force produced by the four fingers, F_{slip} is the minimal grasp force necessary to prevent an object from slipping out of the hand, F_i is the force produced by an individual finger, M_{tot} is the total moment generated by the four normal finger forces, and d_i is the distance between the point of application of a given finger force and the axis of rotation of the 'inverted-T' handle located at the center of the thumb transducer (d_i = +37.5 mm, +12.5 mm, -12.5 mm, and –37.5 mm for the index, middle, ring, and little fingers, respectively. Because the shear force changed as a function of the external torque (see Figure 4.2 in Section 4.1.1 and Figure 4.7 in Section 4.1.3), F_{slip} was different for each load/torque combination. The slip force F_{slip} was estimated as:

$$F_{slip} = F_{shear}/\mu \tag{4.9}$$

where F_{shear} is the largest shear force – either the thumb or all four fingers combined – for a given load/torque combination and μ is the coefficient of static friction (μ = 1.72). The thumb shear force was measured and the shear forces of the fingers were computed as the difference between the total weight of the experimental apparatus (the handle/beam apparatus plus the external load) minus the thumb shear force. The optimization

computations were performed using the ‘linprog’ and ‘fmincon’ functions in the MATLAB Optimization Toolbox (Version 2, The Mathworks, Inc., Natick, MA, USA). The ‘linprog’ function is a variation of the well-known Simplex method for linear programming, while the ‘fmincon’ function uses a sequential quadratic programming technique to find the minimum of a constrained nonlinear multivariable function. The power value p of the cost functions ranged from 1 to 10.

The optimization results presented in Figures 4.14 and 4.15 are for power values of p = 1, 3, and 10. When p = 3, criteria J_2 and J_3 are analogous to the minimum fatigue criterion

$$J = \left(\sum_{i=1}^{9} \left(F_i / PCSA_i \right)^p \right)^{\frac{1}{p}} \rightarrow \min \qquad (p = 2, 3, 4) \tag{4.10}$$

proposed by Crowninshield and Brand (1981) for the muscle sharing problem, the problem of distributing activity among synergistic muscles contributing to a joint moment. In Eq. 4.10, J is the so-called muscle fatigue function, where $PCSA_i$ is the physiological cross-sectional area of the i-th muscle, and the constant p was derived from the experimentally obtained relationship between muscle stress ($F/PCSA$) and endurance time of human muscles (p = 3 on average). This criterion is widely used for studying the muscle sharing problem (for recent reviews, see Herzog, 1996; Prilutsky, 2000; Prilutsky and Zatsiorsky, 2002; Tsirakos *et al*., 1997).

The optimization results for the five cost functions were varied. For zero torque conditions, all five criteria predicted approximately equal involvement of the index-middle and ring-little pairs of fingers that produce pronation and supination moments, respectively, as should be expected (Figure 4.14). Note the large difference between the

actual and predicted forces; there is an unusually large safety margin F_{safe}. Criterion J_1 always predicted equal force production by all four fingers. Criteria J_2 and J_3 predicted relatively greater activation of the 'central' fingers (with the exception of $p = 1$ for criterion J_2), while criteria J_4 and J_5 predicted relatively greater activation of the 'peripheral' fingers. For non-zero torque conditions, the cost functions generally predicted greater force production by the 'peripheral' agonist finger (Figure 4.15). However, criterion J_3 often predicted that the 'central' agonist finger would generate the largest force. Note that the cost functions frequently predicted antagonist moments of force in the 'small torque' (0.375 Nm) condition, while they rarely predicted these moments in the 'large torque' (1.5 Nm) condition.

Root mean square (RMS) error was used as a measure of performance of the optimization criterion; it was calculated as

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}\left(F_i^{pre} - F_i^{exp}\right)^2}{n}} \tag{4.11}$$

where i is an individual finger (I, M, R, or L), n is the total number of fingers involved in a task, F_i^{pre} are the predicted finger forces, and F_i^{exp} are the measured finger forces. The predicted forces were dependent on the power value p of the objective function. Table 4.2 shows the optimal power, defined as the value of p that minimizes the RMS error, for the range of experimental conditions. The RMS error values for a power value of $p = 3$ are presented in Table 4.3. For the five criteria J_1-J_5, criteria J_2 (which minimizes finger forces with respect to the maximal forces measured in single-finger tasks) demonstrated the lowest RMS error values on average.

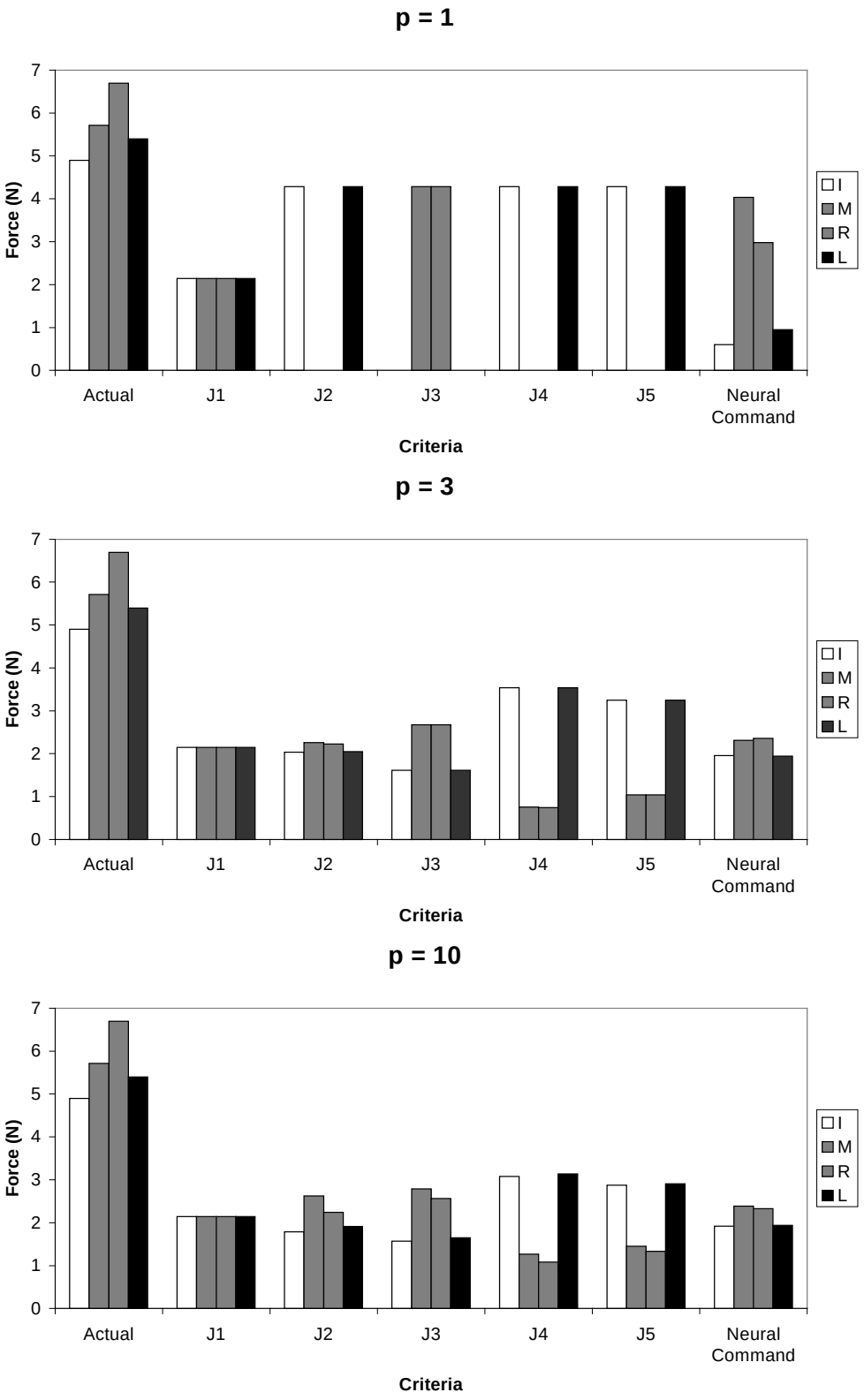


FIGURE 4.14. Actual and predicted (optimal) finger forces (N) for the zero torque condition with an external load of 2.0 kg. Optimization of neural commands will be explained and discussed later in this section.

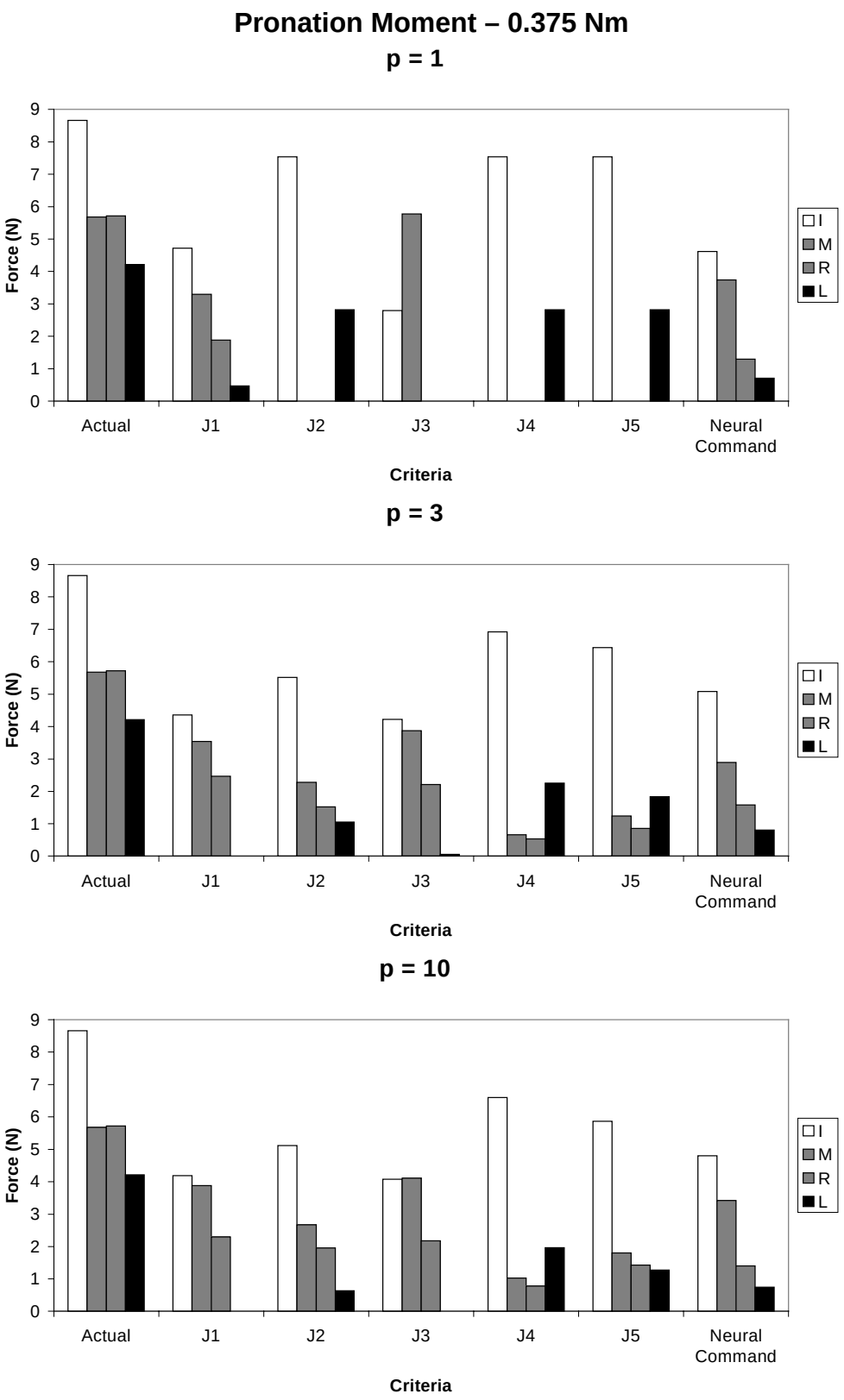


FIGURE 4.15. Comparison of actual force data with force patterns predicted by different optimization criteria for an external load of 2.0 kg.

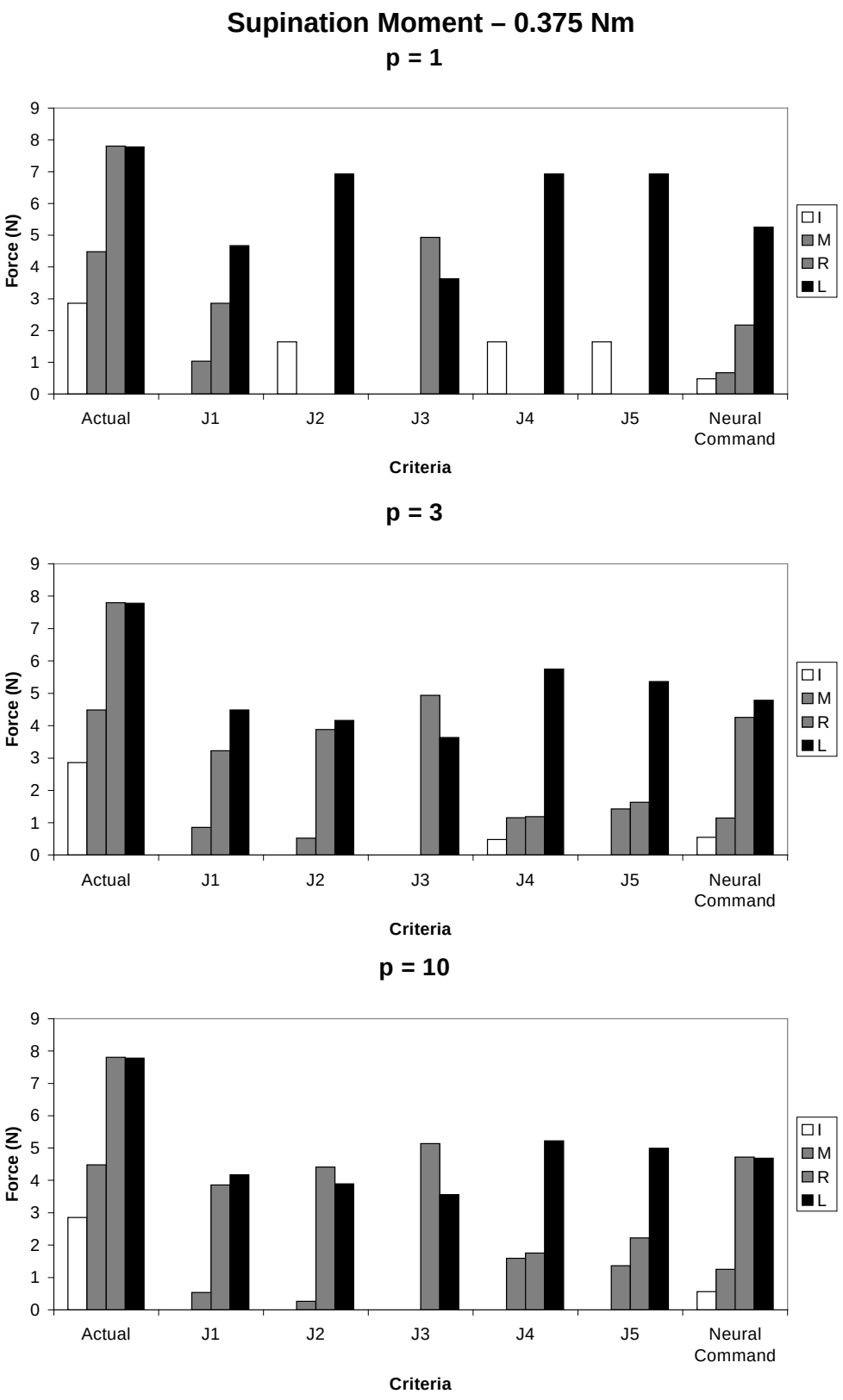


FIGURE 4.15. Con't.

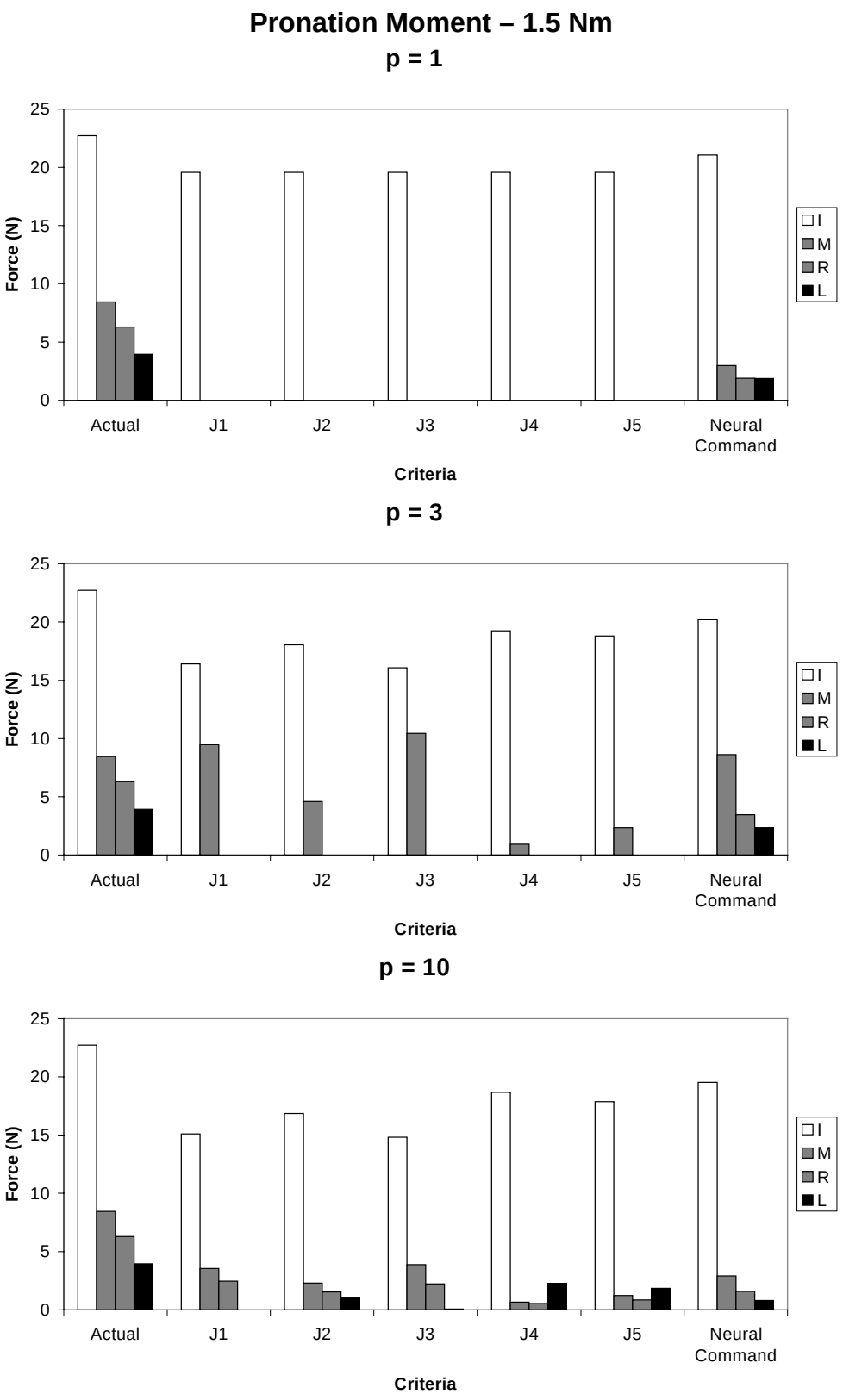


FIGURE 4.15. Con't.

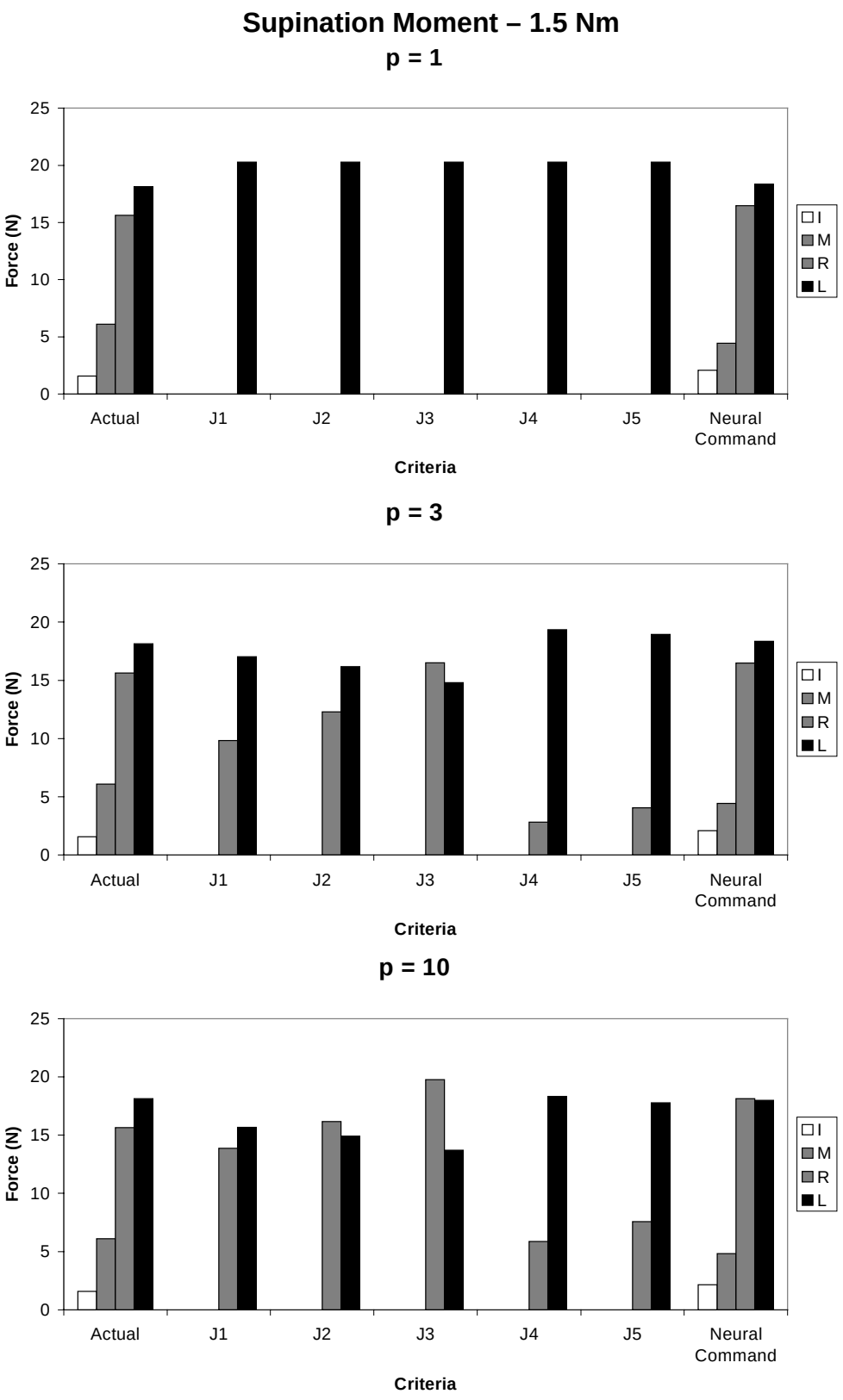


FIGURE 4.15. Con't.

TABLE 4.2. Optimization results – optimal power values, *p* (Pro – pronation, Sup – supination).

		J_1		J_2		J_3		J_4		J_5		*Neural Command*	
Load (kg)	*Torque (Nm)*	*Pro*	*Sup*	*Pro*	*Sup*	*Pro*	*Sup*	*Pro*	*Sup*	*Pro*	*Sup*	*Pro*	*Sup*
0.5	0.375	10	1	4	2	2	2	10	5	10	2	3	5
0.5	0.75	6	2	3	4	2	2	10	10	10	10	2	3
0.5	1.125	5	2	3	3	2	2	10	10	10	8	2	2
0.5	1.5	7	2	4	3	2	2	10	10	10	9	2	2
1.0	0.375	10	1	10	2	4	2	10	10	10	4	10	10
1.0	0.75	8	2	4	4	2	2	10	10	10	10	2	3
1.0	1.125	6	2	3	4	2	2	10	10	10	10	2	3
1.0	1.5	6	2	3	5	2	2	10	10	10	10	2	3
1.5	0.375	10	1	10	2	10	2	10	10	10	10	10	2
1.5	0.75	10	3	6	9	3	2	10	10	10	10	4	6
1.5	1.125	8	2	4	5	2	2	10	10	10	10	2	3
1.5	1.5	10	2	5	6	2	2	10	10	10	10	2	3
2.0	0.375	10	1	3	9	2	2	10	10	10	10	10	2
2.0	0.75	10	3	10	10	3	3	10	10	10	4	10	10
2.0	1.125	10	3	6	9	3	2	10	10	10	10	4	5
2.0	1.5	10	2	5	5	3	2	10	10	10	10	2	3
Average		8.5	1.9	5.2	5.1	2.9	2.1	10.0	9.7	10.0	8.6	4.3	4.1

TABLE 4.3. Optimization results – RMS values, N (Pro – pronation, Sup – supination).

		J_1		J_2		J_3		J_4		J_5		*Neural Command*	
Load (kg)	*Torque (Nm)*	*Pro*	*Sup*	*Pro*	*Sup*	*Pro*	*Sup*	*Pro*	*Sup*	*Pro*	*Sup*	*Pro*	*Sup*
0.5	0.375	2.25	1.40	2.18	1.31	2.28	1.34	2.12	1.98	2.12	1.86	1.59	0.61
0.5	0.75	2.80	1.84	2.58	1.65	2.91	1.90	2.82	3.17	2.69	2.89	1.41	0.65
0.5	1.125	3.40	1.90	2.84	1.70	3.63	2.47	3.21	4.01	2.99	3.57	1.41	1.42
0.5	1.5	3.99	2.57	3.19	1.90	4.32	2.51	3.81	5.79	3.46	5.17	1.57	1.92
1.0	0.375	2.78	2.05	2.58	1.89	2.84	1.75	2.58	2.68	2.54	2.56	2.31	1.03
1.0	0.75	3.22	1.91	3.11	1.68	3.30	1.85	3.36	3.28	3.24	3.00	1.82	0.55
1.0	1.125	3.52	2.64	3.13	2.37	3.71	2.78	3.57	4.60	3.33	4.19	1.42	1.03
1.0	1.5	3.75	3.12	3.51	2.71	3.99	3.33	4.44	5.90	4.00	5.33	1.00	1.63
1.5	0.375	2.69	2.94	2.53	2.85	2.77	2.65	2.75	3.27	2.61	3.18	2.59	1.98
1.5	0.75	3.65	2.76	3.73	2.49	3.68	2.42	4.07	4.03	3.92	3.77	2.31	0.91
1.5	1.125	3.91	3.19	3.84	2.87	4.04	3.06	4.38	5.11	4.12	4.71	1.79	1.01
1.5	1.5	4.24	4.83	4.28	3.17	4.41	3.18	5.23	6.78	4.80	6.20	1.44	1.21
2.0	0.375	3.59	3.68	3.51	3.62	3.63	3.66	3.84	4.02	3.68	3.89	3.51	3.08
2.0	0.75	4.39	3.65	4.51	3.36	4.39	3.12	4.61	4.89	4.49	4.64	3.12	1.70
2.0	1.125	4.69	3.66	4.84	3.19	4.76	3.00	5.42	5.75	5.16	5.34	2.66	0.86
2.0	1.5	4.90	4.32	4.79	3.69	5.08	3.59	5.56	7.16	5.20	6.60	2.07	0.97
Average		3.61	2.84	3.45	2.53	3.73	2.66	3.86	4.53	3.65	4.18	2.00	1.29

4.2.2. Reconstruction of Neural Commands

Due to finger enslaving (Zatsiorsky *et al*., 1998, 2000), a flexion command sent to a given finger causes force production by other fingers.

4.2.2.1. Neural Network Modeling of Finger Forces: Inter-Finger Connection Matrices

The interdependence among fingers during force production has been addressed in previous research (Zatsiorsky *et al*., 1998, 2000). Subjects were instructed to press as hard as possible on force sensors with either one, two, three, or four fingers acting in parallel using all possible combinations. A neural network model simulating the muscular apparatus of the hand was developed (Figure 4.16). The model consists of three layers: (1) the input layer that models a central neural drive; (2) the hidden layer that

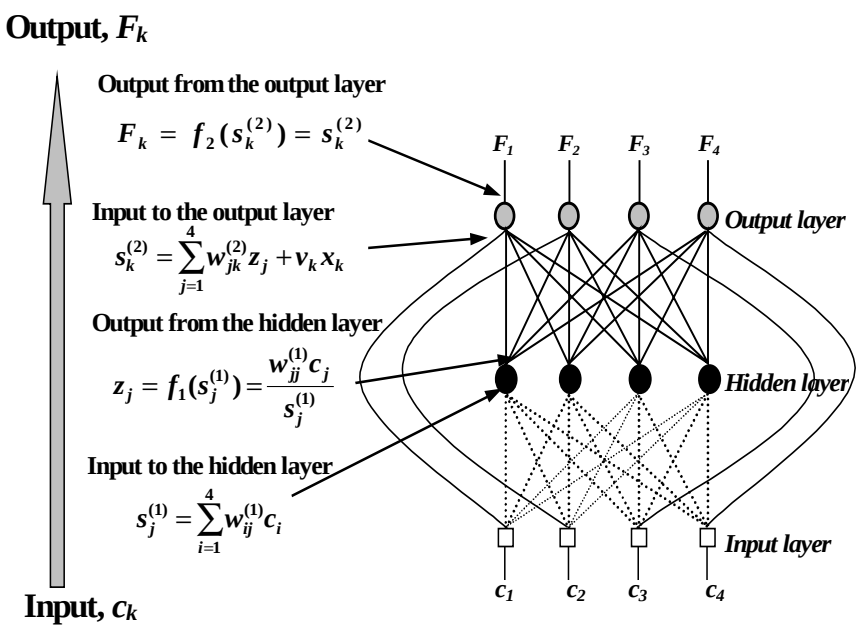


FIGURE 4.16. Neural network model and associated mathematical formulations. The index, middle, ring, and little fingers correspond to 1, 2, 3, and 4, respectively. The background of the network is explained in Zatsiorsky *et al*. (1998). The network was validated using three different training sets and performed remarkably well. In all cases, the predicted finger forces were in the range of ± 1 standard deviation.

simulates transformation of the central drive into an input signal to the muscles serving several fingers simultaneously (e.g., multi-digit muscles), and (3) the output layer representing finger force output. The output of the hidden layer is set inversely proportional to the number of fingers involved. The network also features direct connections between the input and output layers that represent signals to the hand muscles serving individual fingers (e.g., single-digit muscles). In this model, the input values (*central commands*) were set at either 1 if the finger was intended to produce force or 0 if the finger was not intended to produce force.

The neural network yielded an association between the neural commands and the individual finger forces. The relationship between the central commands and the finger forces was expressed as a matrix equation:

$$[F] = \frac{1}{n}[w][c] + [v][c] \tag{4.12}$$

where $[F]$ is the (4×1) vector of finger forces, $[w]$ is the (4×4) matrix of weight coefficients (the matrix models interconnections among the fingers, both central and peripheral connections at the muscle-tendon level), $[c]$ is the (4×1) vector of dimensionless neural commands (a single element of the vector represents the intensity of the command sent to a given finger), $[v]$ is the (4×4) diagonal matrix with gain coefficients that model the input-output relationships for single-digit muscles, and n is the number of fingers that are intended to produce force (for these fingers, central command = 1). The values of $[w]$ and $[v]$ were found to be

$$[w] = \begin{bmatrix} 32.7 & 9.1 & 3.8 & 3.7 \\ 14.2 & 29.0 & 13.6 & 3.5 \\ 9.0 & 20.2 & 22.4 & 10.9 \\ 8.8 & 7.6 & 16.0 & 17.2 \end{bmatrix} \text{and } [v] = \begin{bmatrix} 16.9 & 0 & 0 & 0 \\ 0 & 10.1 & 0 & 0 \\ 0 & 0 & 8.3 & 0 \\ 0 & 0 & 0 & 7.2 \end{bmatrix}. \tag{4.13}$$

For a given *n*, Eq. 4.11 can be reduced to

$$[F] = [W][c] \tag{4.14}$$

where [*W*] is the (4 × 4) matrix of weight coefficients (*inter-finger connection matrix*). From Eq. 4.13, it follows that a command c_i sent to a finger *i* (*i* = 1, 2, 3, or 4) activates all other fingers to a certain extent (*enslaving effects*). The force exerted by a given finger *i* is the result of a summation of the command sent to this finger as well as the commands sent to other fingers.

4.2.2.2. Method of Reconstruction and Results

If the vector of finger forces [*F*] and weight matrix [*W*] are known, the vector of neural commands can be determined by inverting Eq. 4.14. The vector of neural commands is then

$$[c] = [W]^{-1}[F]. \tag{4.15}$$

The vector [*F*] was measured in this study. The weight matrix [*W*] was taken from previous research on neural network modeling of force production by several fingers (Zatsiorsky *et al*., 1998). The weight matrix [*W*] is

$$[W] = \begin{bmatrix} 25.08 & 2.28 & 0.95 & 0.93 \\ 3.55 & 17.35 & 3.40 & 0.88 \\ 2.25 & 5.05 & 13.90 & 2.28 \\ 2.20 & 1.90 & 4.00 & 11.50 \end{bmatrix}. \tag{4.16}$$

In the study of Zatsiorsky *et al*. (1998), the group average of the sum of the individual maximal finger forces was 141.8 N. In the present study, the subjects were able to produce larger maximal forces on average; the sum of the individual finger forces was 178.2 N. Therefore, a correction coefficient of 178.2/141.8 = 1.2566 was introduced

and the weight matrix [W] was multiplied by this coefficient. The adjusted weight matrix $_a[W]$ is

$$_a[W] = [W] \times 1.2566 = \begin{bmatrix} 31.52 & 2.87 & 1.19 & 1.17 \\ 4.46 & 21.80 & 4.27 & 1.11 \\ 2.83 & 6.35 & 17.47 & 2.87 \\ 2.76 & 2.39 & 5.03 & 14.45 \end{bmatrix}. \tag{4.17}$$

The elements of this matrix are the finger forces induced by neural commands of maximal intensity (c_j = 1). In particular:

(1) Any element on the main diagonal is equal to the force produced by finger i (i = 1, 2, 3, or 4) induced by a command of unit intensity to this finger; for example, a command to the index finger c_{index} = 1 results in a force of 31.5 N.

(2) The rows of the matrix represent the force of a given finger induced by commands to all of the fingers; for example, when commands of unit intensity are sent to all of the fingers the little finger generates a force of 24.7 N (2.8 + 2.4 + 5.0 + 14.5), of which only 14.5 N comes from the command sent to this finger and the remaining 10.2 N (2.8 + 2.4 + 5.0) are due to enslaving.

(3) The columns of the matrix correspond to the effect of a command c_i = 1 sent to a given finger on all four fingers; for example, the second column represents the finger forces induced by a command of unit intensity sent to the middle finger. Such a command results in forces of 2.87 N, 21.80 N, 6.35 N, and 2.39 N being produced by the index, middle, ring, and little fingers, respectively.

Any element ij of the matrix is equal to the force of finger i in response to a maximal command sent to finger j (c_j = 1). The inverse of the adjusted weight matrix $_a[W]$ is

$$ {}_{a}[W]^{-1} = \begin{bmatrix} 0.0325 & -0.0038 & -0.0007 & -0.0022 \\ -0.0060 & 0.0501 & -0.0116 & -0.0010 \\ -0.0024 & -0.0173 & 0.0649 & -0.0113 \\ -0.0044 & -0.0015 & -0.0205 & 0.0737 \end{bmatrix}. \tag{4.18} $$

The neural commands computed from Eq. 4.15 are presented in Table 4.4. The obtained commands, as expected, generally ranged from 0 to 1. In one case, a command to the little finger during a supination effort exceeded 1 slightly. For the large supination moments, the commands to the index finger were slightly less than 0, which may represent a small extension command or simply be a result of inaccuracies in the neural network model. Taking into account that the neural command intensities were computed by combining the results of three experiments, (1) the study of Zatsiorsky *et al*. (1998), (2) force measurements during torque production tasks (Section 4.1.4), and (3) maximal force measurements (Section 4.1.5), the accuracy of the reconstruction can be considered reasonable. The commands sent to individual fingers changed systematically with the magnitude and direction of the external torque. During the largest pronation moments (resulting from an external CW torque of 1.5 Nm), the commands to the index finger varied from 0.658 to 0.694, i.e., the index finger was never maximally activated. In contrast, during the largest supination moments (resulting from an external CCW torque of –1.5 Nm), the commands to the little finger varied from 0.948 to 1.037, i.e., the little finger was activated close to maximally.

4.2.2.3. Neural Commands and Finger Forces

The relationship between neural command intensities and finger forces (expressed as a percentage of the maximal force in a single-finger task) is presented in Figure 4.17. When the fingers produced agonist moments, the intensity of the commands was larger

TABLE 4.4. Neural commands to the individual fingers for the experimental load and torque conditions (maximal command intensity = 1; absence of command = 0).

		0.5 kg Load		
Torque (Nm)	*Index*	*Middle*	*Ring*	*Little*
-1.5	-0.035	0.030	0.601	0.948
-1.125	-0.006	0.016	0.415	0.830
-0.75	0.006	0.014	0.311	0.580
-0.375	0.023	0.023	0.192	0.326
0	0.074	0.042	0.105	0.102
0.375	0.215	0.056	0.077	0.061
0.75	0.375	0.082	0.067	0.050
1.125	0.490	0.110	0.055	0.046
1.5	0.689	0.140	0.044	0.037
		1.0 kg Load		
Torque (Nm)	*Index*	*Middle*	*Ring*	*Little*
-1.5	-0.028	0.064	0.584	1.037
-1.125	-0.010	0.035	0.449	0.857
-0.75	0.002	0.026	0.324	0.581
-0.375	0.027	0.043	0.233	0.308
0	0.094	0.067	0.158	0.124
0.375	0.210	0.079	0.110	0.129
0.75	0.378	0.087	0.127	0.056
1.125	0.531	0.117	0.082	0.045
1.5	0.661	0.206	0.093	-0.034
		1.5 kg Load		
Torque (Nm)	*Index*	*Middle*	*Ring*	*Little*
-1.5	-0.036	0.085	0.665	0.959
-1.125	-0.015	0.089	0.470	0.828
-0.75	0.004	0.046	0.376	0.601
-0.375	0.029	0.074	0.297	0.335
0	0.117	0.123	0.201	0.181
0.375	0.231	0.110	0.155	0.084
0.75	0.385	0.139	0.131	0.086
1.125	0.516	0.171	0.142	0.058
1.5	0.658	0.238	0.129	0.025
		2.0 kg Load		
Torque (Nm)	*Index*	*Middle*	*Ring*	*Little*
-1.5	-0.024	0.130	0.686	0.997
-1.125	-0.009	0.083	0.553	0.778
-0.75	0.015	0.102	0.425	0.621
-0.375	0.055	0.109	0.333	0.395
0	0.121	0.173	0.262	0.238
0.375	0.248	0.164	0.203	0.146
0.75	0.388	0.182	0.187	0.101
1.125	0.556	0.211	0.161	0.045
1.5	0.694	0.209	0.145	0.045

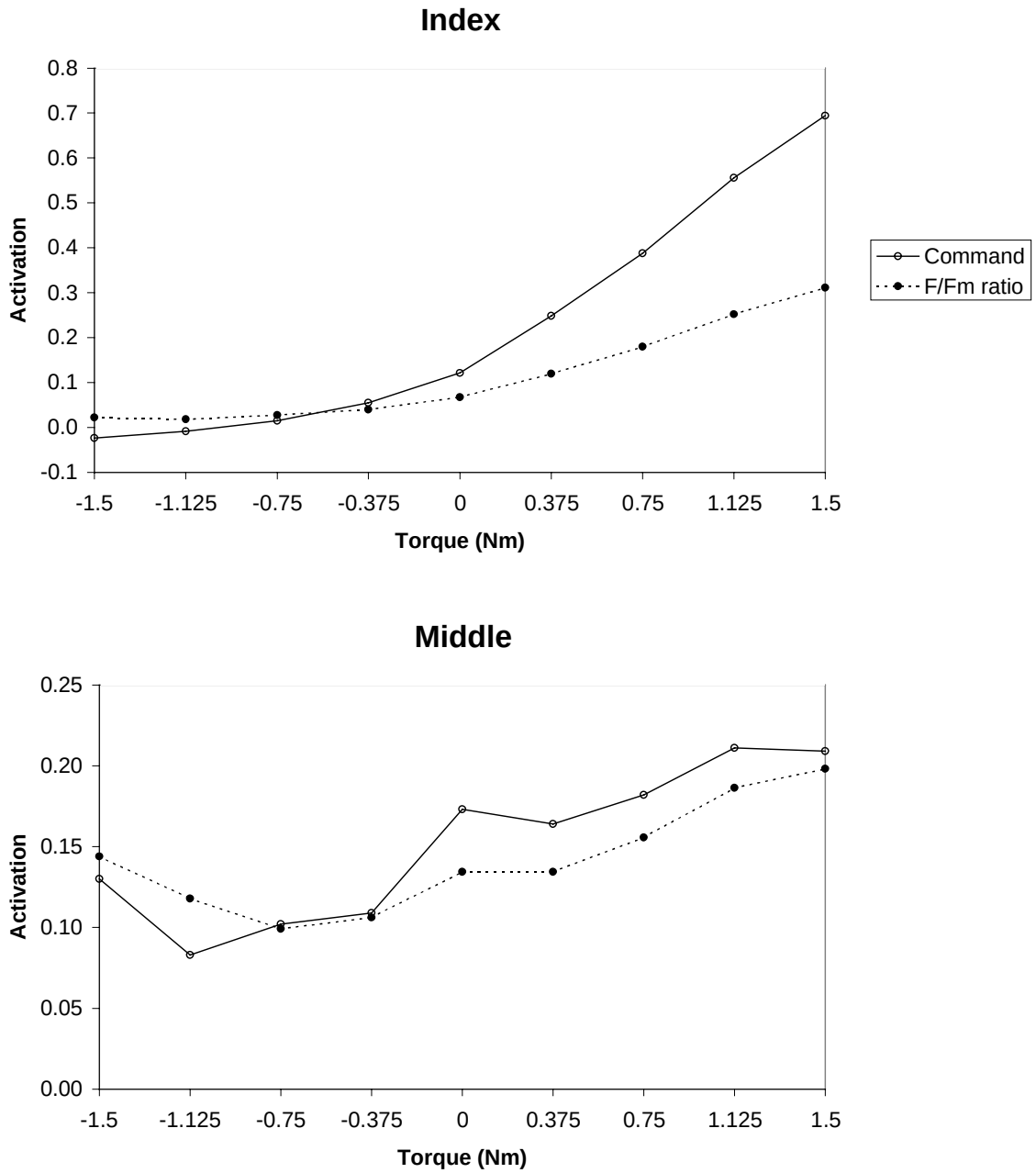
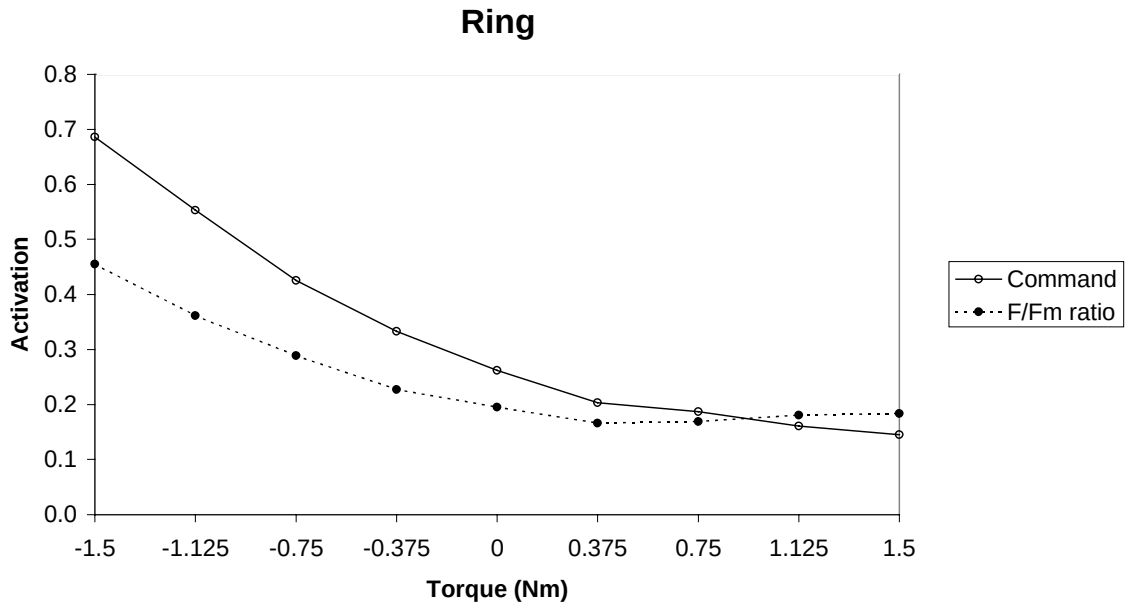


FIGURE 4.17. Representative examples for command intensity and relative finger forces (F_i/F_{imax} ratio: finger force/maximal force in a single-finger task) for the 2.0 kg load condition.



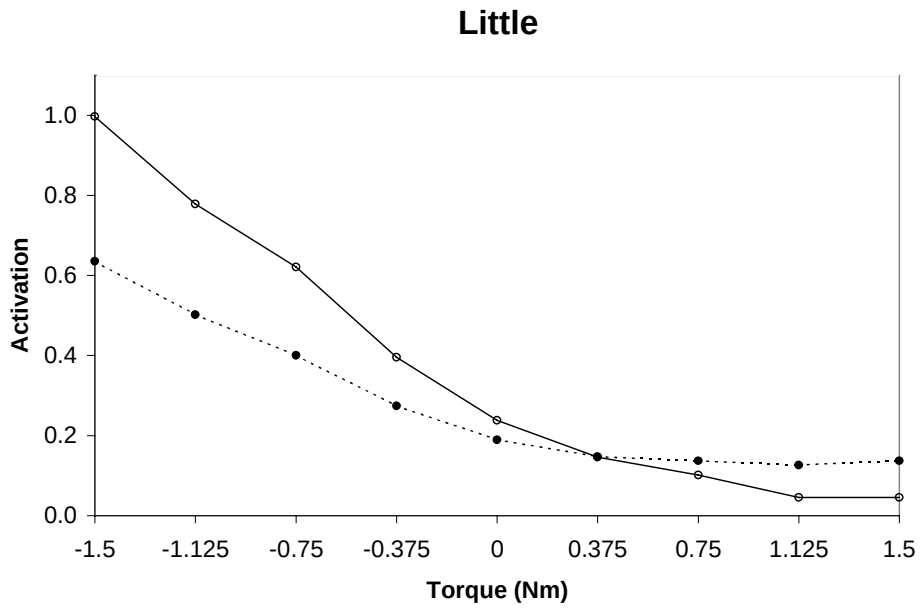


FIGURE 4.17. Con’t.

than the relative force while the opposite was true for the production of antagonist moments. The point at which the curves intersected was close to, but not exactly at, zero torque. When the finger forces were expressed as a percentage of the maximal forces measured in a four-finger task, the correspondence between the command intensity and the relative finger forces improved (Figure 4.18). The improvement obtained in modeling finger force production using the neural network model as compared to optimization techniques is evidently due to the enslaving effects that are neglected in optimization criteria J_1-J_5 but are accounted for in the neural command approach. Enslaving effects are relatively larger when a finger acts as a torque antagonist and produces a smaller force.

4.2.2.4. Decompositon of Finger Forces: Examination of Enslaving Effects

The force generated by a given finger results from the command sent to this finger ('direct' finger force) as well as from the commands sent to other fingers (enslaved force). The direct finger forces can be computed as the product $w_{ii}c_i$ (i = 1, 2, 3, or 4), where w_{ii} is a diagonal element of ${}_a[W]$ (Figure 4.19). The difference between the actual and direct finger forces represents enslaving effects, i.e., the force produced by a finger due to the commands sent to other fingers. The enslaved forces are presented in Figure 4.20.

The minimum enslaved force occurs at or close to zero torque for the middle, ring, and little fingers. Note that the rather irregular behavior of the middle finger forces (Figure 4.19) is associated with a smooth, regular dependence of the enslaved forces resulting from the external torque (Figure 4.20). This method allows for partitioning the effects of enslaving on individual fingers due to the commands sent to each of the fingers.

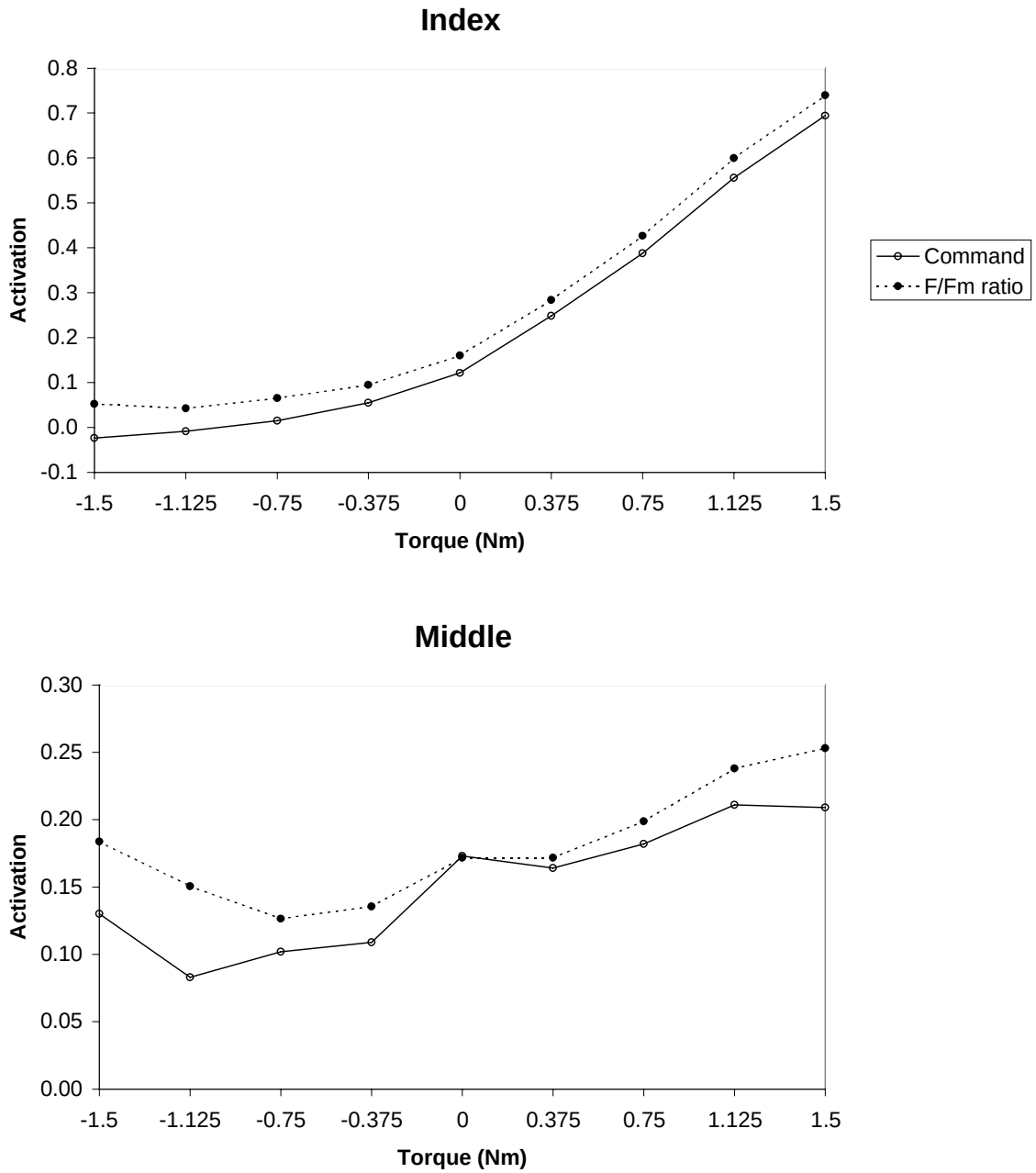
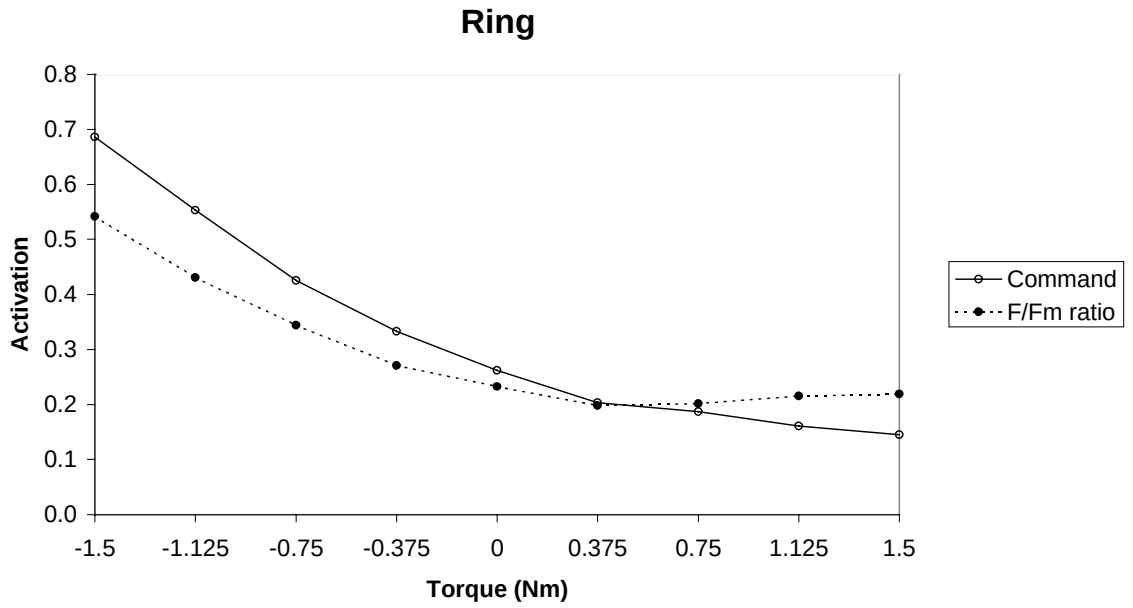


FIGURE 4.18. Central commands and relative finger forces (expressed as a percentage of the maximal finger force in a four-finger grip task) for the 2.0 kg load condition.



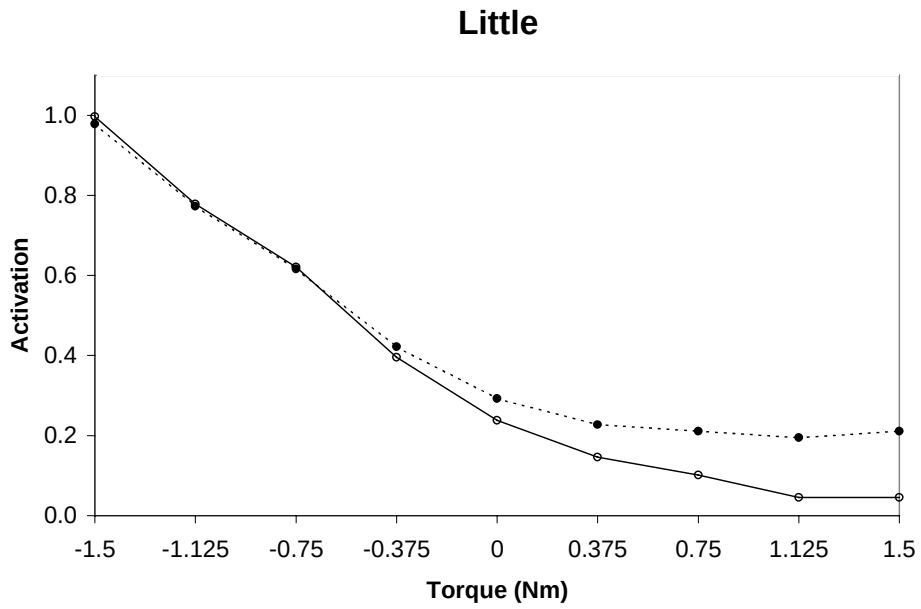


FIGURE 4.18. Con’t.

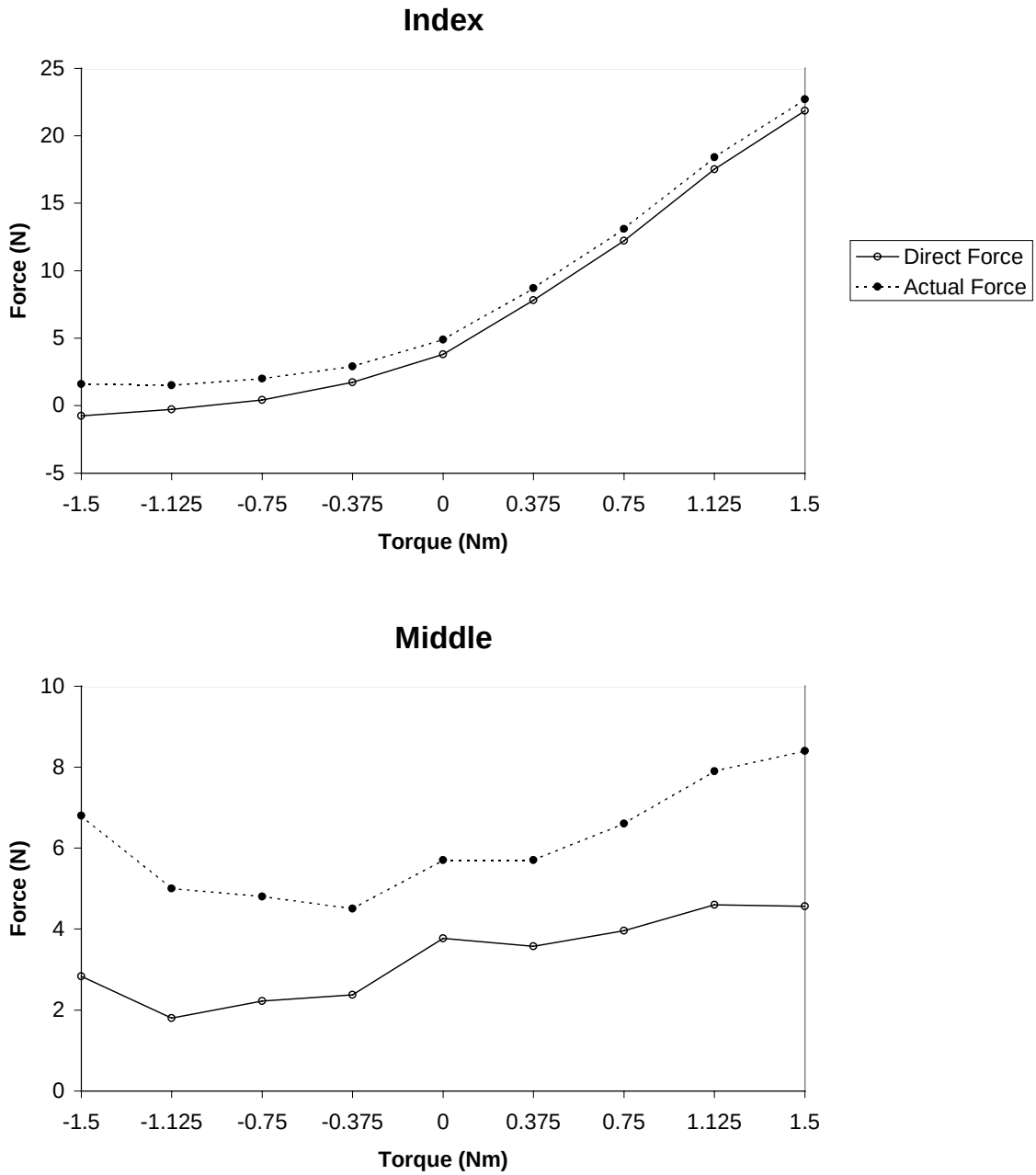
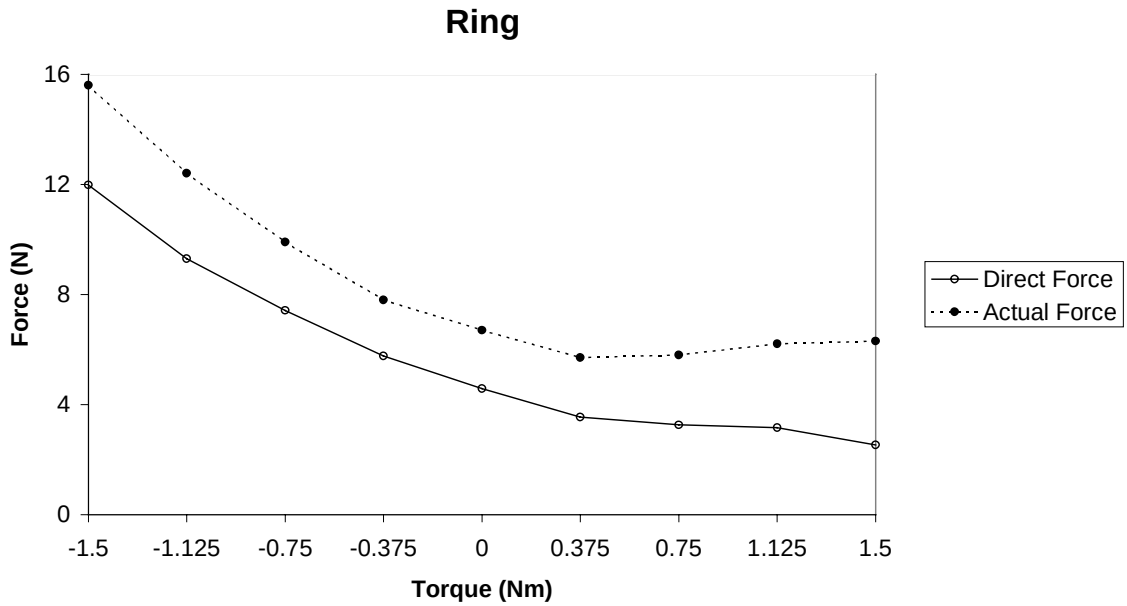


FIGURE 4.19. Actual and 'direct' finger forces (N) for a 2.0 kg load as a function of external torque. The direct forces were computed as the products of the diagonal elements of the matrix of the connection weights w_{ii} (i = 1, 2, 3, or 4) times the corresponding finger commands c_i.



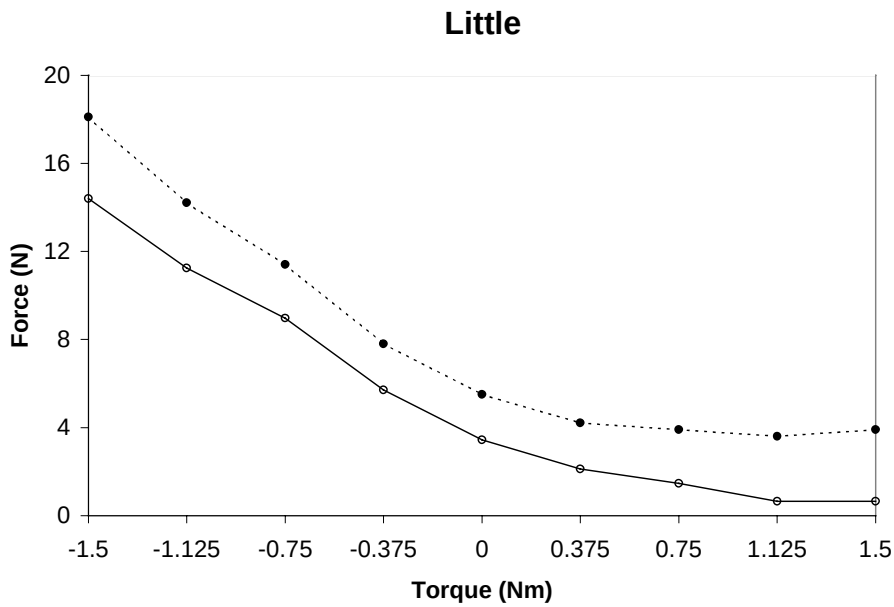


FIGURE 4.19. Con't.

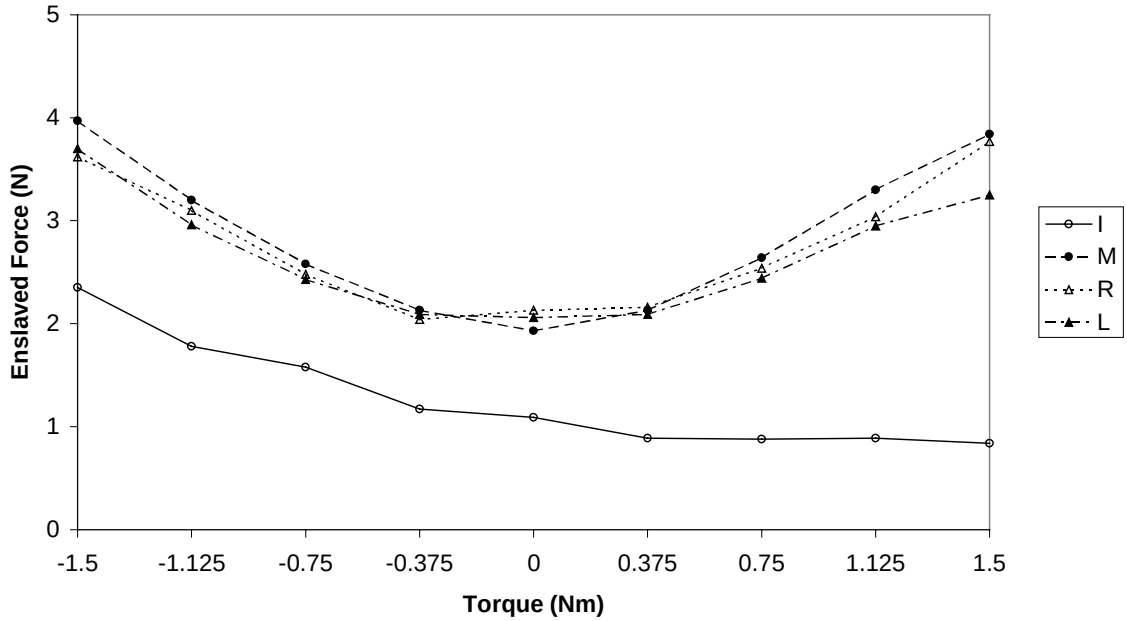


FIGURE 4.20. Enslaved force (N) for a 2.0 kg load as a function of external torque for the index, middle, ring, and little fingers.

An example of such a decomposition is presented in Figure 4.21. The summed effects from the index, ring, and little fingers are equal to the enslaved force (r = 0.998).

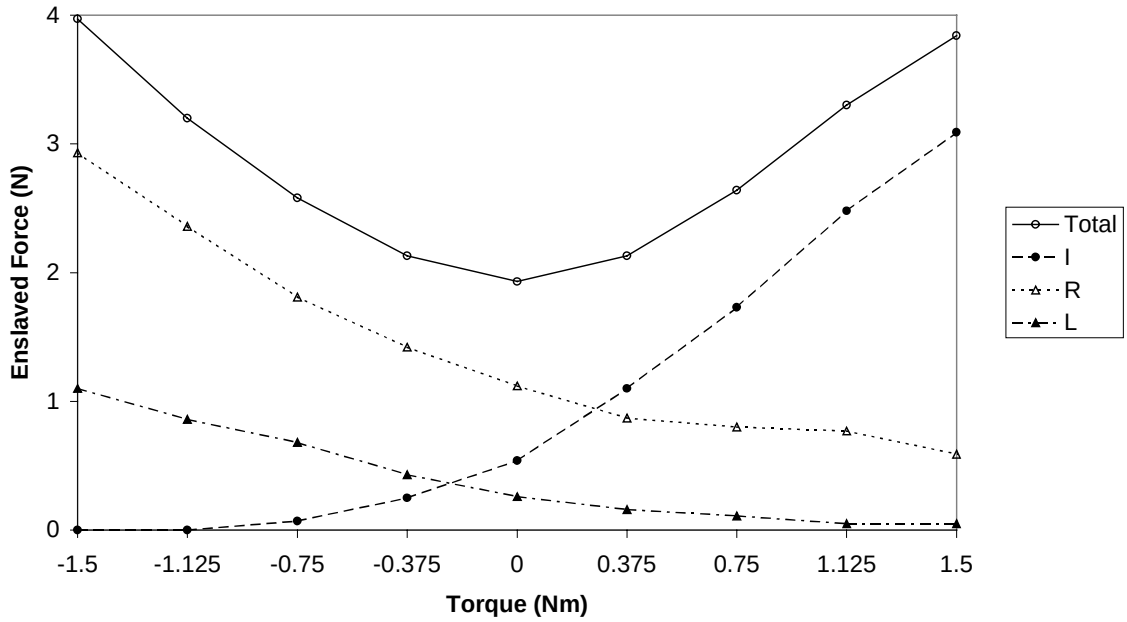


FIGURE 4.21. Decomposition of enslaving effects due to activation of the middle finger for a 2.0 kg load as a function of external torque.

4.2.3. Optimization of Central Commands

In addition to optimization of finger forces, optimization of neural commands was also performed. The following objective function was optimized:

$$J_6 = \left(\sum_{i=1}^{4} (c_i)^p \right)^{\frac{1}{p}} \rightarrow \min \qquad (p = 1, 2, \ldots 10) \tag{4.19}$$

where the constraint $[c] = {}_a[W]^{-1}[F]$ was used in addition to the previously mentioned constraints in Eq. 4.8. Root mean square (RMS) error was used as a measure of performance of this criterion (see Table 4.3). Overall, criterion J_6 performed much better than criteria J_1-J_5. In all 32 load/torque combinations with non-zero external torques, the RMS values were smaller for the optimization of neural commands. On average, the RMS values for the cost function based on neural commands equaled only 55%, 58%, 54%, 52%, and 55% for criteria J_1, J_2, J_3, J_4, and J_5, respectively, in pronation tasks, and 45%, 51%, 48%, 28%, and 31% of the RMS values for criteria J_1, J_2, J_3, J_4, and J_5, respectively, in supination tasks. In addition, criterion J_6 always predicted antagonist moments while the other criteria often failed to predict them (see Figure 4.15). An obvious reason for the better performance of the criterion based on neural commands is that it accounts for enslaving effects while the other criteria do not.

CHAPTER 5
DISCUSSION

In this study, the normal forces exerted by the fingers were measured during static force and torque production tasks. In addition, the normal and shear forces produced by the thumb were also recorded. The subjects were required to hold a handle in a vertically-oriented position without any visible planar or rotational movements. The lack of motion of the handle demonstrates that the acceleration of the handle was small and did not influence the balance of forces and moments. Hence, the fingers produced a given total moment of force with respect to the thumb – the torque due to the total normal and shear forces was equal in magnitude and opposite in direction to the external torque.

5.1. BIOMECHANICS OF FORCE AND TORQUE PRODUCTION

As follows from Figures 4.1-4.13. there are regularities in the way finger forces are coordinated according to the requirements of the task. The necessity of some of the finger activation patterns, particularly the reason behind antagonist moments, is not clear. Antagonist moments should be counterbalanced by increased force from the agonist fingers; therefore, any antagonist moment increases the total force production. Such a coordination pattern does not appear to be optimal. The first issue to consider is whether antagonist moments are mechanically necessary?

5.1.1. MECHANICALLY NECESSARY AND UNNECESSARY ANTAGONIST MOMENTS

As follows from basic mechanics, maintaining the ‘inverted-T’ handle in a position of static equilibrium requires that the following conditions be satisfied: (1) the

sum of the normal finger forces is equal and opposite in magnitude to the force of the thumb; (2) the sum of the shear forces produced by the fingers and thumb is equal to the total weight of the handle and external load; and (3) the sum of the moments generated by the fingers is equal to the torque, $Torque = M_{tot} + M_{shear}$, where M_{shear} is the moment created by the shear forces. Also, the sum of the normal forces of the four fingers should be sufficiently large to prevent slipping, $F_{tot} > F_{slip}$.

The shear forces produced by the individual fingers and the moments produced by these forces were not measured in this study. However, the contribution of the total moment of the four normal finger forces M_{tot} to the torque is almost constant for all load/ torque combinations, $M_{tot}/Torque = constant$ (see Figure 4.3). It is presumed that the central controller selects a specific value of M_{tot} for any load/torque combination; then, the controller still has some freedom in selecting a particular combination of finger forces. The magnitude of M_{tot} was computed from regression equations relating the moment of the normal forces produced by the fingers to the torque created by the external load (Section 4.1.2). For example, the moment of the normal finger forces for a load of 2.0 kg and a torque of 1.5 Nm is $M_{tot} = 0.504(Torque) – 0.01 = 0.746$ Nm. For such a load/torque combination the constraints are $M_{tot} = 0.746$ Nm and $F_{tot} > F_{slip}$.

When only the agonist fingers produce force the constraint equations are:

$$F_1 + F_2 = F_{tot} > F_{slip} \tag{5.1a}$$

$$0.125F_1 + 0.375F_2 = M_{tot} \tag{5.1b}$$

where F_1 and F_2 are the normal forces generated by a ‘central’ (middle or ring) finger and a ‘peripheral’ (index or little) finger, respectively. The latter equation can be transformed into

$$F_1 + 3F_2 = M_{tot}/0.125 = F_{mom} \tag{5.1c}$$

where F_{mom} has a dimensionality of force. Due to the simplicity of these equations, it is convenient to analyze them graphically (Figure 5.1). The bold line in Figure 5.1 corresponds to the equation $F_1 + F_2 = constant$ while the three thin lines correspond to Eq. (5.1c) for three different values of F_{mom}. The force-force combinations above the bold line provide a safe grip while combinations below the line will result in the object slipping from the hand. Those force-force combinations that are: (a) above the line $F_1 + F_2 = constant$, and (b) on the line $F_1 + 3F_2 = F_{mom}$ satisfy the task requirements.

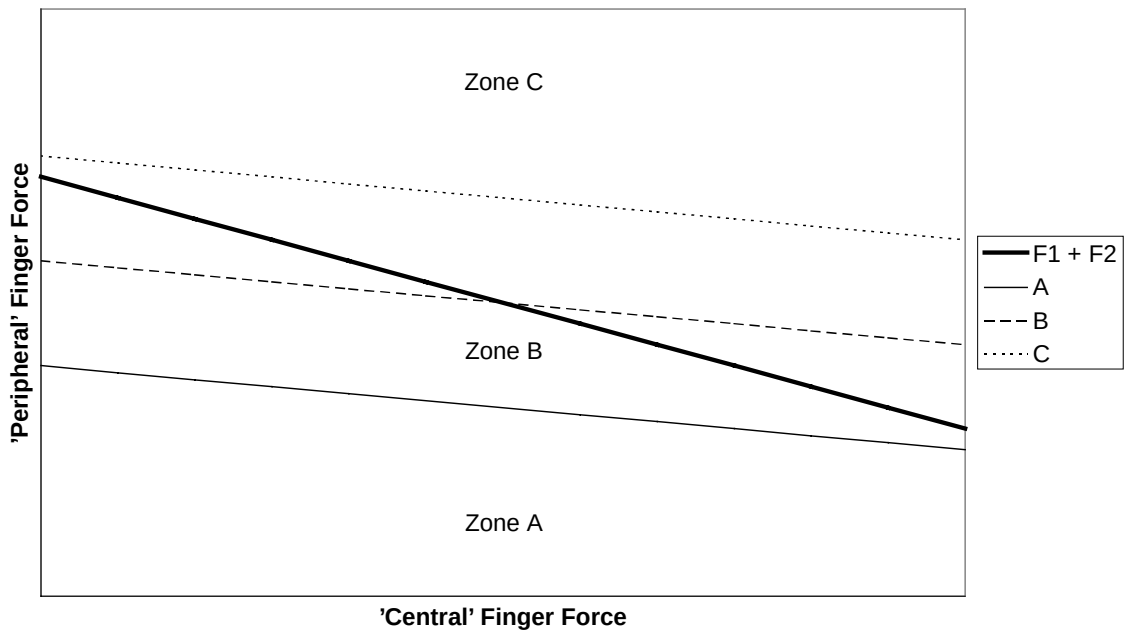


FIGURE 5.1. Finger forces at different load/torque combinations (see explanation in text). The bold line represents the equation $F_1 + F_2 = constant$. The lines A, B, and C correspond to the force-force combinations that produce moments in zones A, B, and C, respectively.

From Figure 5.1, it is evident that three possible load/torque combinations exist (a *three-zone model* of prehension):

(A) *Large load/small torque* combinations. The line for F_{mom} is below the line for $F_1 + F_2 = constant$ over the entire range of force-force values. The only option to prevent slipping is to activate antagonist fingers and, hence, produce an antagonist moment. Such an antagonist moment is *mechanically necessary*.

(B) *Intermediate load/intermediate torque* combinations. The line for F_{mom} is below the line for $F_1 + F_2 = constant$ in the left part of the graph where F_1 values are small and it is in the non-slip range in the right part of the graph where F_1 values are large. To prevent slipping, an individual has two options: either (a) exert larger force with the agonist 'central' finger while simultaneously decreasing the force of the agonist 'peripheral' finger such that the relationship $F_1 + 3F_2 = F_{mom}$ is maintained, or (b) activate antagonist fingers. If an individual utilizes option (a), antagonist moments are not necessary.

(C) *Small load/large torque* combinations. The line for F_{mom} is above the line for $F_1 + F_2 = constant$ over the entire range of force-force values. There is no need for the individual to be concerned about the object slipping from the hand: any force-force combination that satisfies the equation $F_1 + 3F_2 = F_{mom}$ is sufficient to prevent slippage. In this range, antagonist moments are not necessary.

The slip force is $F_{slip} = F_{threshold}/\mu$, where $F_{threshold}$ is the minimum shear force necessary to prevent slippage and μ is the coefficient of static friction. When the external torque is zero, the shear force of the thumb is equal to approximately one-half of the total supported weight (the weight of the handle/beam apparatus plus the external load). The thumb shear force exceeds 50% of the weight during supination efforts, while the shear force is smaller during pronation efforts (see Figure 4.2). Hence, the shear force

generated by all four fingers is less than 50% of the total weight force during supination efforts and exceeds this value during pronation efforts. When the shear force increases F_{slip} also increases; therefore, F_{slip} depends not only on the force but also on the torque (Zatsiorsky *et al*., 2002a). In addition, individual fingers may produce forces in different directions; the shear force/normal force ratio may be different for different fingers (Li, 2002). Hence, each finger has its own F_{slip}. When the shear force resisted by individual digits increases the digit slip force, i.e., the digit normal force necessary to prevent slipping of the digit, also increases. Therefore, F_{slip} of individual digits depends not only on the supported load but also on the torque. Because the shear forces produced by the fingers were not recorded, the ability to apply the proposed three-zone model to actual data is limited. Therefore, Figure 5.1 should only be regarded as a schematic representation of a general concept. Based on this figure, it is possible to conclude that increasing F_{slip} (moving the bold line upward) should result in shifting some load/torque combinations from zone B into zone A and from zone C into zones A and B.

5.1.2. THE THREE-ZONE MODEL VS. ACTUAL DATA

During ‘large load/small torque’ combinations, antagonist moments are mechanically necessary (zone A). In this range, slippage cannot be prevented without activation of *torque antagonists*, i.e., fingers that produce antagonist moments. Contrary to this, activation of antagonist fingers is not necessary during ‘small load/large torque’ combinations; the normal forces generated by the agonist fingers are sufficient for preventing slips (zone C). Nevertheless, antagonist moments were observed in all three zones. This implies that non-mechanical factors have an effect on individual finger forces in such tasks.

5.1.3. Basic Biomechanics of Prehension

Fingers produce both normal and shear forces during torque production (see Figures 4.4 and 4.7). During pronation efforts, the shear force of the thumb decreased with the external torque; consequently, the shear force of the fingers increased (Figure 5.2). The opposite was true for supination efforts. Because decreased shear forces increase the risk of slipping, normal forces must increase to prevent a slip from occurring. In order to maintain static equilibrium, the normal forces of the thumb and fingers must be equal in magnitude. Therefore, the normal forces of the thumb and fingers always increased or decreased in conjunction with each other. This explains the results observed during pronation/supination efforts in which the normal forces were large and the force/torque

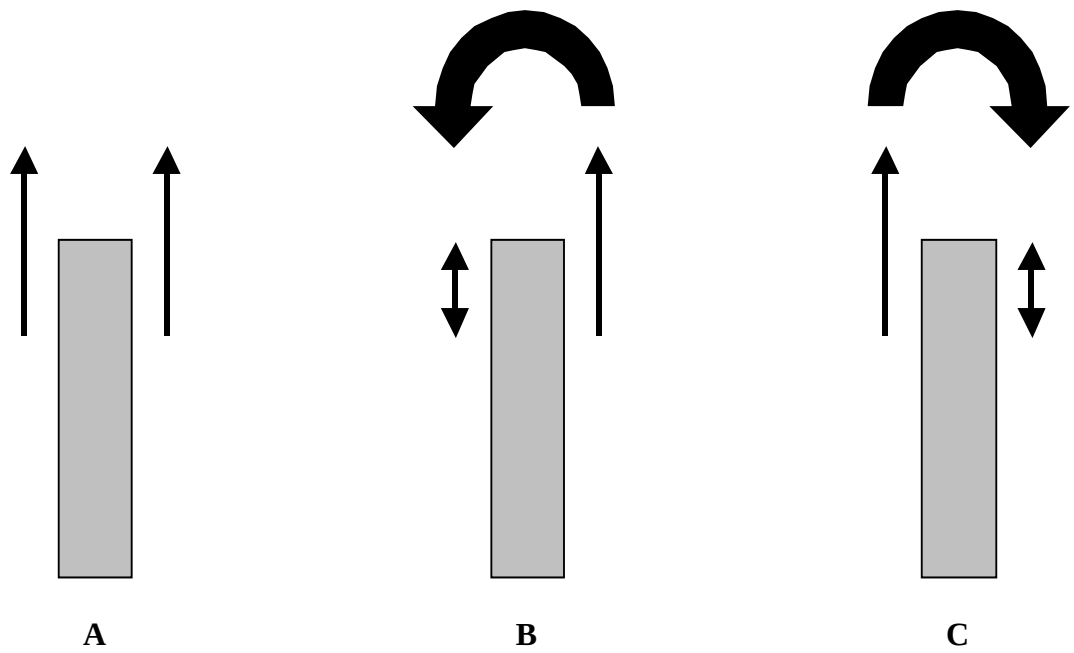


FIGURE 5.2. Schematic of shear forces during torque production. (A) No torque: the shear forces of the thumb and fingers are approximately equal. (B) Pronation torque: the shear force of the fingers is larger than the shear force of the thumb. The thumb shear force may be zero or negative. (C) Supination torque: the shear force of the thumb exceeds the shear force of the fingers. The shear force of the fingers may be zero or negative. In all three cases, the sum of the shear forces is equal to the total weight of the hand-held object.

curves were approximately symmetric with respect to the zero torque conditions (see Figure 4.4).

The moment produced by the normal finger forces is generated by two mechanisms: (a) changing the sharing pattern and, consequently, the displacement of the point of application of the resultant force, and (b) increasing the magnitude of the resultant force. The first mechanism was predominant for the smaller torques (0.375 Nm and 0.75 Nm), while the point of force application did not change substantially for the larger torques (1.125 Nm and 1.5 Nm) and the increase in moment production was achieved by an increase in force magnitude.

5.1.4. Individual Finger Forces: Dependence on the Mechanical Advantage

There was a monotonic relationship between the mechanical advantage of a finger (i.e., its moment arm during torque production) and the force produced by that finger. This relationship, however, was not linear (Figure 5.3). In addition, individual fingers were activated according to their mechanical advantage. During pronation/supination efforts, the agonist 'peripheral' fingers with larger moment arms were activated to a larger extent than the agonist 'central' fingers with smaller moment arms (see Figures 4.8-4.12). The forces F_i, force sharing values S_i, and force actualization values A_i produced by the fingers were significantly correlated with their mechanical advantage (the finger moment arm with respect to the axis of rotation). The average correlation (across all 16 pronation/supination condition) between F_i, S_i, $A_{i/I}$, and $A_{i/IMR}$ and moment arm was $r = 0.78$, $r = 0.82$, $r = 0.44$, and $r = 0.58$, respectively, for the pronation efforts, and $r = 0.85$, $r = 0.89$, $r = 0.84$, and $r = 0.82$, respectively, for the supination efforts. The correlation between finger activation and moment arm was lower during pronation

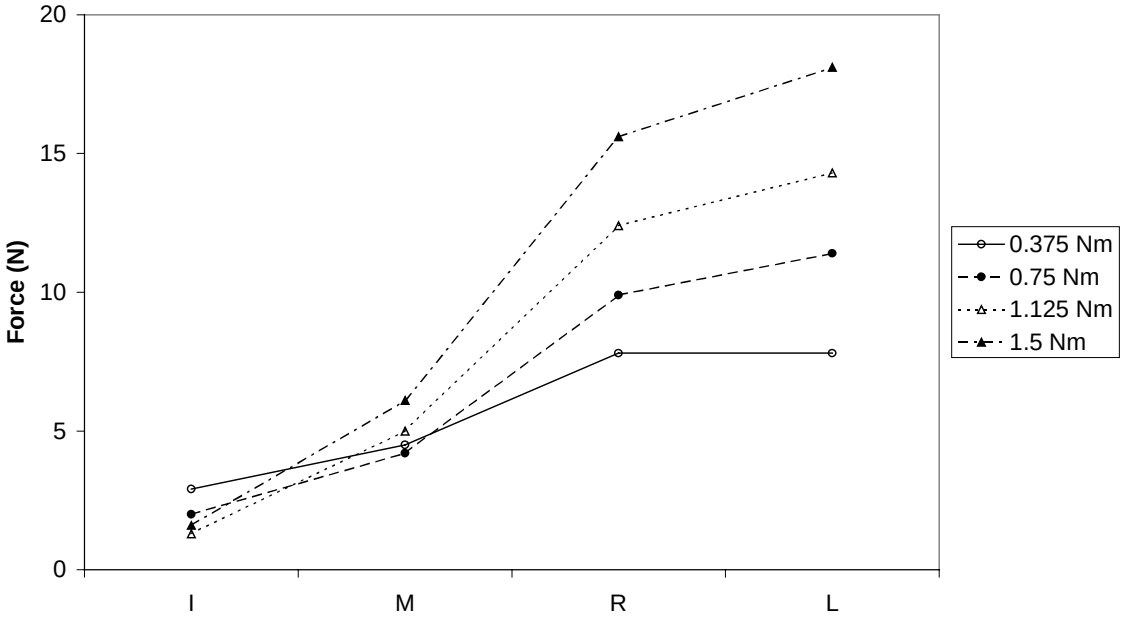


FIGURE 5.3. Relationship between finger force and finger location during supination moments for a 2.0 kg load. The letters I, M, R, and L represent the index, middle, ring, and little fingers, respectively. The distance between the fingertip centers of adjacent fingers was 25 mm. Note that in all conditions the largest force is produced by the little finger, which generates a smaller maximal force than the ring finger.

moments as compared to supination moments due to the rather irregular behavior of the middle finger forces.

Because a set of five digits is redundant for the control of a hand-held object, the effort can be distributed among the involved fingers in many different ways. It has been either experimentally observed or routinely assumed that the central nervous system activates muscles (or fingers in this particular case) according to their mechanical advantage, which is determined by the amount of mechanical effect per unit of muscle force produced. The concept of mechanical advantage as it pertains to muscles may be considered from three different perspectives: (1) the different magnitudes of muscle moment arms; (2) the projection of the moment of force generated by an individual

muscle on the axis of rotation required by the motor task (Haar Romeny *et al*. 1984, Jongen *et al*. 1989, Buchanan *et al*. 1986, Buchanan *et al*. 1989, Buchanan *et al*. 1993); and (3) the advantage of activating two-joint muscles versus one-joint muscles (Prilutsky and Gregor 1997, Prilutsky 2000). For this study, only the first two perspectives are relevant.

It is hypothesized that the CNS activates individual muscles in proportion to their moment arms. It has been reported that the EMG activity of a one-joint muscle is proportional to its moment arm at the joint (Buchanan *et al*., 1986; Flanders and Soechting, 1990; Jacobs and Ingen Schenau, 1992; Kuo, 1994; Nichols 1994). In biomechanical modeling of muscle activity, the principle of *minimal total muscle force* is often used. This principle means that no more total muscular force is used than is both necessary and sufficient to maintain a joint's motor action. The consequence of this principle is that the muscles with the largest moment arms are preferentially recruited. The results obtained in this study support the hypothesis that the CNS activates individual muscles in proportion to their moment arms: individual fingers were activated according to their mechanical advantage. Although the limitations of the minimal total muscle force principle have been recognized by a number of investigators (Crowninshield and Brand, 1981a, b; Dul *et al*., 1984a, b), it is still a part of many biomechanical models of muscle force sharing.

The regularities in the patterns of finger forces suggest that neural factors do not simply represent random choices with equal probabilities from an acceptable set of solutions. Evidently, the CNS uses an additional set of criteria to make such a choice. In the next section, different approaches to identifying these criteria based on the current

data set and previously published experimental and modeling studies (Zatsiorsky *et al*., 1998) will be discussed.

5.2. CONTROL OF FORCE AND TORQUE PRODUCTION

This study has demonstrated that phenomena such as force deficit and enslaving originally discovered in maximal pressing tasks also exist in sub-maximal precision grip tasks involving torque production. The inter-finger weight matrices serve as quantitative estimates of these effects. The force deficit is accounted for by a coefficient $1/n$, where n is the number of fingers involved in the task (see Eqs. 4.12 and 4.14) and enslaving is represented by the elements of the matrix. These matrices relate neural commands with finger forces and allow for the reconstruction of neural commands from known finger force values.

5.2.1. THE REASONS BEHIND ANTAGONIST MOMENTS

In Section 5.1.1 a three-zone model for prehension was introduced. It was demonstrated that antagonist moments in zone A are mechanically necessary. The reason for their existence in zones B and C are less clear. Consider the optimization results for criteria J_1-J_5 with a power value of $p = 3$. For non-zero torque conditions, none of the cost functions predicted antagonist moments of force, with the exception of the 2.0 kg/0.375 Nm load/torque combination (Figure 4.15). This ‘large load/small torque’ combination evidently corresponds to zone A of the three-zone model, a zone where antagonist moments are a mechanical necessity. Hence, criteria based on minimization of finger forces fail to predict the existing antagonist moments observed in zones B and C,

where they are not mechanically necessary. According to these criteria, the force distribution patterns employed by the subjects were not optimal.

One of the possible mechanisms that results in antagonist moments in zones B and C is enslaving; antagonist fingers are activated because strong commands are sent to agonist fingers and antagonist fingers are enslaved by these commands. The computation of neural commands and their effects supports this hypothesis (see Figures 4.17-4.21). The neural commands to antagonist fingers produced in response to large external torques are close to zero or even negative. For example, the neural commands to the index finger were negative in the 1.125 Nm and 1.5 Nm supination moment conditions. Nevertheless, antagonist fingers were active and generated force due to enslaving.

A second, purely hypothetical mechanism may also contribute to the production of antagonist moments. The experimental tasks utilized in this study required a high degree of accuracy; subjects were asked to maintain the handle in a vertically-oriented position. Antagonist muscles are usually active during static precision tasks (Osu and Gomi, 1999). The co-activation of the muscles that generate opposite movements at a joint (e.g., flexion-extension) increases the apparent joint stiffness (i.e., the resistance of the joint to a perturbation) (however, see Burnett *et al*., 2000). It seems reasonable to assume that antagonist moments are produced for similar reasons, namely to improve the accuracy of the system and increases its resistance to perturbations. This hypothesis can be tested by changing the accuracy requirements of the task, e.g., allow the handle to deviate up to 10° from vertical and/or change the moment of inertia of the experimental apparatus.

5.2.2. WHAT ARE NEURAL COMMANDS?

In Zatsiorsky *et al*. (1998), as well as in this study, neural commands were introduced and used in a purely operational way, i.e., simply as a means for computing the commands and describing the relationship between the commands and finger forces. The commands are sets of neural parameters (something that we do not know) that assume a maximal value (1) when a maximal voluntary contraction is required and a minimal value (0) when voluntary force is not generated. Because matrix methods are used to describe the relationship between neural commands and finger forces, this relationship is also implicitly assumed to be linear. The methods utilized in this study do not provide a means for establishing the actual physiological mechanisms behind these abstract concepts.

Neural commands, however, may have real physiological meaning. Tax and Denier van der Gon (1991) suggested that muscle force may linearly depend on neural control signals without violating such well-known phenomena as the size principle (Henneman *et al*., 1965a, b) and non-linear twitch summation (Burke *et al*., 1976). Consider a motoneuron pool that receives input from a nerve bundle. The weighted sum of activities in a nerve bundle I is

$$I = \sum_i u_i e_i \tag{5.2}$$

where I is the control signal of a motoneuron pool, e_i is the firing frequency of action potentials traveling along each nerve fiber in the bundle, and u_i is the synaptic weight of a nerve fiber i projecting to a motoneuron. Note that in this model, it is assumed that the synaptic weights for all motoneurons are equal. When some commonly accepted physiological principles (i.e., different recruitment density of small and large motor units)

are incorporated into the model, a linear relationship between the control signal *I* and force produced by a muscle is established. Hence, the control signal *I* is proportional to the force produced by a muscle and can be interpreted as an internal representation of muscle force. While the neurophysiological mechanisms of the neural commands analyzed in this study remain unclear, there is a certain similarity between these commands and the control signals *I* to motoneuron pools (Eq. 5.2).

5.2.3. INTER-FINGER WEIGHT MATRICES

The inter-finger weight matrix [*W*] worked remarkably well in this study; in particular, the neural commands were determined with sufficient accuracy. This outcome deserves to be noted because, as previously mentioned, the computation of the neural commands was based on empirical data from three separate experiments performed on two groups of subjects (Zatsiorsky *et al*., 1998 and this study). This implies that the matrix is robust and, after the necessary adjustment for differences in maximal finger force production of the subject groups, may be used for different populations. Obviously, this assertion needs to be tested experimentally. For future studies, it seems reasonable to use normalized weight matrices (per 1 N of total finger force measured in single-finger tasks)

$$ {}_{n}[W] = \frac{1}{\sum F_i(\max)}[W]. \tag{5.3} $$

The inter-finger weight matrix [*W*] introduced in Eq. 4.14 models enslaving effects, while Eq. 4.12 models both enslaving and force deficit. Another way to analyze enslaving effects is to utilize set theory and Venn diagrams. For example, let *I* and *M* be anatomical objects (e.g., individual muscles, muscle bundles, motoneuron pools, or

populations of supra-spinal neurons) defining the magnitude of the forces produced by the index and middle fingers, respectively. Then, if the intersection of sets *I* and *M* is not empty $(I \bigcap M \neq 0)$, the union of *I* and *M* contains a smaller number of elements than *I* and *M* combined $[I \bigcup M < (I + M)]$. The intersection $I \bigcap M$ specifies the amount of enslaving while the difference $(I + M) - I \bigcup M$ specifies the amount of force deficit. The intersection $I \bigcap M$ represents an overlap of the anatomical objects serving two fingers, e.g., the muscle bundles in the extrinsic hand muscles that serve multiple fingers.

Recent research demonstrates that muscle bundles as well as individual muscles are not very good candidates for explaining enslaving effects. This conclusion was drawn from experiments in which the site of finger force application was varied and the forces were exerted at either the distal or proximal phalanges (Li *et al*., 2001). When the point of force application was at the distal phalanx, the extrinsic flexor muscles were the major contributors to finger force production. However, when the force was applied at the proximal phalanx, the intrinsic group was the major contributor. In spite of different muscle involvement, enslaving did not depend on the site of force application and was approximately the same when the forces were exerted at the distal or proximal phalanges (Zatsiorsky *et al*., 2000). It appears that it is not musculo-tendinous interconnections, but rather higher-order interactions that define enslaving effects.

In the human primary somatosensory cortex, cortical digit representations are arranged from the lateral inferior aspect to the medial superior aspect in anatomical order – the thumb, followed by the index, middle, ring, and little fingers (Baumgartner *et al*., 1991). However, the volumes representing individual fingers overlap extensively (Krause *et al*., 2001). Increases in the activated volumes of both single finger and

overlapping representations occur following an increase in stimulus intensity. In the primary motor cortex of monkeys, neuronal populations activated by movements of different fingers also overlap in their spatial locations (Schieber and Hibbard, 1993). The control of any finger movement utilizes a distributed population of neurons and the activity of the entire neuronal population specifies particular finger movements (Georgopoulos *et al*., 1999). It appears that the phenomena of force deficit and enslaving have their origin at this level, rather than being completely defined by musculo-tendinous connections at the peripheral level. It would be interesting to map out the relationship – if it even exists – between the inter-finger connection matrices and the overlapping volumes of population neurons.

5.2.4. Finger Redundancy and Muscle Redundancy

There is a certain similarity between finger coordination in multi-finger manipulative tasks and muscle coordination in joint moment production (Li *et al*., 1998a, b; Zatsiorsky *et al*., 1998). Both fingers and muscles work in parallel (Zatsiorsky, 2002). In statics, parallel systems are redundant and described by under-determined sets of equations: the number of unknowns is larger than the number of available equations. For example, the number of muscles typically exceeds the number of degrees of freedom for a given joint. In kinematics, parallel systems are over-constrained and described by over-determined sets of equations: the number of equations exceeds the number of unknowns. For instance, if the length of one single-joint muscle is known, the joint angle and lengths of the other muscles spanning that joint can be determined. Similarly, when an object is grasped, the same force and torque can be exerted on the object by different combinations

of digit forces while the position of each finger is uniquely defined by the configuration of the other fingers.

The similarities that are evident between these two systems prompt one to question whether or not the central nervous system controls these mechanically similar systems in a similar way. Studying finger coordination during multi-finger prehension is an advantageous method for analyzing the force sharing problem; contrary to the direct measurement of muscle-tendon forces, finger forces can easily be measured. In particular, the question arises whether enslaving exists at the level of muscles. In other words, can the hypothetical central controller activate one muscle independently of other muscles? In numerous reviews of the force sharing problem (Herzog, 1996; Prilutsky and Zatsiorsky, 2002; Tsirakos *et al*., 1997), possible enslaving effects are completely neglected when different optimization approaches are used. In conjunction with previously published findings (Li *et al*., 1998a,b; Zatsiorsky *et al*., 1998, 2000), the results of this study question this approach.

5.3. SUMMARY AND CONCLUSIONS

The present study addressed forces exerted by five digits on a hand-held object during static force and torque production tasks. First, it was observed that individual finger forces F_i, force sharing values S_i, and force actualization values A_i were dependent on both the external load and torque. Second, it was demonstrated that there was a monotonic relationship between the mechanical advantage of a finger (i.e., its moment arm during torque production) and the force produced by that finger. Third, force sharing patterns utilized during torque production tasks appear to be sub-optimal. All five optimization criteria based on the minimization of finger forces failed to predict

antagonist finger moments when these moments were not imposed by the task mechanics. Optimization of neural commands resulted in the best correspondence between the actual and predicted finger forces. Finally, this study demonstrated that phenomena such as force deficit and enslaving originally discovered in maximal pressing tasks also exist in sub-maximal precision grip tasks involving torque production.

The findings in this study can be viewed as consequences of two major groups of constraints: (1) those defined by the mechanics of the task; and (2) those defined by central nervous system (CNS) strategies. In order to prevent handle rotation, the individual fingers should produce normal and shear forces of such magnitudes that the moment of force with respect to the pad of the thumb equals zero. Hence, the forces produced by individual fingers and the force sharing pattern are at least partly defined by mechanical constraints. However, the regularities in the patterns of digit forces suggest that the neural factors do not simply represent random choices with equal probabilities from a mechanically acceptable set of solutions. Apparently, the CNS uses an additional set of criteria to make such a choice.

As with all experimental studies, the conclusions must be analyzed and interpreted with prudence. The findings obtained in this study are valid only for young males and no other age or gender groups. In addition, the precision grip task was performed utilizing only the dominant hand. All participants used the same experimental apparatus and were subjected to the same external loads and torques; no attempt was made to customize the design of the experimental apparatus for each subject or normalize the experimental tasks according to each individual's maximal force and torque generating capability. Perhaps the most important limitation of the study was the use of

uni-axial force transducers to measure the forces produced by the index, middle, ring, and little fingers. As previously noted, the contact points between the digits and force transducers can displace during grasping; this has significant implications for calculating the moment arms of the individual fingers about the axis of rotation created by the thumb. Also, uni-axial force transducers are not able to provide any information regarding the shear forces produced by individual fingers. In this study, fingers were classified as producing either an agonist moment (a moment of force in the intended direction of the total moment) or an antagonist moment (a moment of force in the opposite direction of the total moment) based on the normal forces produced by the fingers. However, it is possible that a finger could produce a normal force that creates an antagonist moment, while at the same time generating a shear force that results in an agonist moment.

5.4. FUTURE DIRECTIONS

The study of the biomechanics and motor control of force and torque production during multi-finger prehension provides many opportunities for future research. For instance, the paradigm used in the present study can be repeated with different age groups, genders, and clinical populations. Also, because different subjects have different maximal strengths, it would be appropriate to normalize the external loads and torques for the individual subjects. Due to differences in the force sharing patterns between the dominant and non-dominant hands, it is also advisable to use the current paradigm with the non-dominant hand. The limitations of using uni-axial force transducers to measure digit forces have been noted; to truly elucidate the functions of the individual fingers, it is essential to use six-axis force/torque transducers. This will allow the determination of the actual contact points between the digits and the force transducers, which will allow a

more accurate evaluation of the relationship between the mechanical advantage of a given finger and the force produced by that finger. Six-axis force/torque transducers will enable us to gain a better understanding of the normal and shear forces produced by individual fingers during simultaneous force and torque production tasks. Finally, in order to improve the design of hand prostheses, robotic hands, and hand-held tools and work equipment, it is suggested that the digit forces be measured during activities of daily living and occupational tasks to determine the forces typically produced by the fingers.

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APPENDIX A

INFORMED CONSENT FORM

INFORMED CONSENT FORM FOR CLINICAL RESEARCH STUDY

The Pennsylvania State University

Title of Project: Motor Redundancy in Multi-Finger Tasks (980494-00)

Principal Investigators: Vladimir M. Zatsiorsky, Mark L. Latash, Robert W. Gregory

Other Investigators: Karl M. Newell, Zong-Ming Li

Contact: Vladimir M. Zatsiorsky, Ph.D.
Director, Biomechanics Laboratory
39 Recreation Building
University Park, PA 16802
(814) 865-3445

This is to certify that I,_____, have been given the following information with respect to my participation as a volunteer in a program of investigation under the supervision of Dr. Vladimir M. Zatsiorsky.

1. **Purpose of the study:**
   Hand function can be considered as an example of how the central nervous system solves the motor redundancy problem. When a task is to produce a certain mechanical effect by activating several fingers, e.g., to generate a required force or torque, the effort can be distributed among the involved fingers in many different ways. Two considerations, a general and a specific one, inspired this study. From a general perspective, the idea is to study the problem of motor redundancy using the fingers as a convenient object. From a more specific standpoint, hand and finger function itself is worthy of study.

2. **Procedures to be followed:**
   Subjects will be asked to produce force with the fingers of their dominant hand by pressing on a cylinder-shaped device connected to a force sensor. Subjects will be asked to produce forces of varying magnitudes (up to maximal force) and use various one-, two-, three-, and four-finger combinations. The forces of the individual fingers and the combined force produced by all of the fingers involved in a given task will be registered during the experiment. Surface electromyography data will be recorded during force production by placing electrodes on the skin to measure the activity level of various muscles in the hand and forearm.

3. **Discomforts and risks:**
   There are no discomforts or risks associated with participation in this experiment for healthy people (those people with no history of traumas to or neuropathies of the upper limbs). Force generation above a certain level can be painful for patients with hand disorders. Patients will be asked to generate forces below this level.

4. a. **Benefits to me:**
      Subjects will have the opportunity to learn about various experimental techniques and methods used in biomechanics and motor control research. In addition, patients will gain a greater understanding of hand disorders.
   b. **Potential benefits to society:**
      The methods developed have potential use as diagnostic tools in clinical settings. They will enable clinicians to test muscle function in the hand and to identify existing musculoskeletal weaknesses and imbalances. This has implications in regards to diagnosing and monitoring both musculoskeletal problems and neurological disorders.

5. **Alternative procedures which could be utilized:**
   N/A.

6. **Time duration of the procedures and study:**
   Each session will last between one and two hours. Subjects will participate in one to three sessions.

7. **Statement of confidentiality:**
   All records associated with my participation in this study will be subject to the usual confidentiality standards applicable to medical records (e.g., such as records maintained by physicians, hospitals, etc.), and in the event of any publication resulting from the research no personally identifiable information will be disclosed.

8. **Right to ask questions:**
   I have been given an opportunity to ask any questions I may have, and all such questions or inquiries have been answered to my satisfaction.

9. <u>Compensation</u>:
I understand that medical care is available in the event of injury resulting from research but that neither financial compensation nor free medical treamtment is provided. I also understand that I am not waving any rights that I may have against the University for injury resulting from negligence of the University or investigators. Questions regarding this statement or your rights as a subject should be directed to the Office for Regulatory Compliance, The Pennsylvania State University, 212 Kern Graduate Building, University Park, PA 16802-3301 (814-865-1775).

10. <u>Voluntary participation</u>:
I understand that my participation in this study is voluntary, and that I may withdraw from this study at any time by notifying the investigator. My withdrawal from this study or my refusal to participate will in no way affect my care or access to medical services.

11. In the event that abnormal test results are obtained, you will be appraised of the results and recommended to contact your private medical provider for follow-up.

This is to certify that I consent to and give permission for my participation as a volunteer in this program of investigation. I understand that I will receive a signed copy of this consent form. I have read this form, and understand the content of this consent form.

_____

Volunteer Date

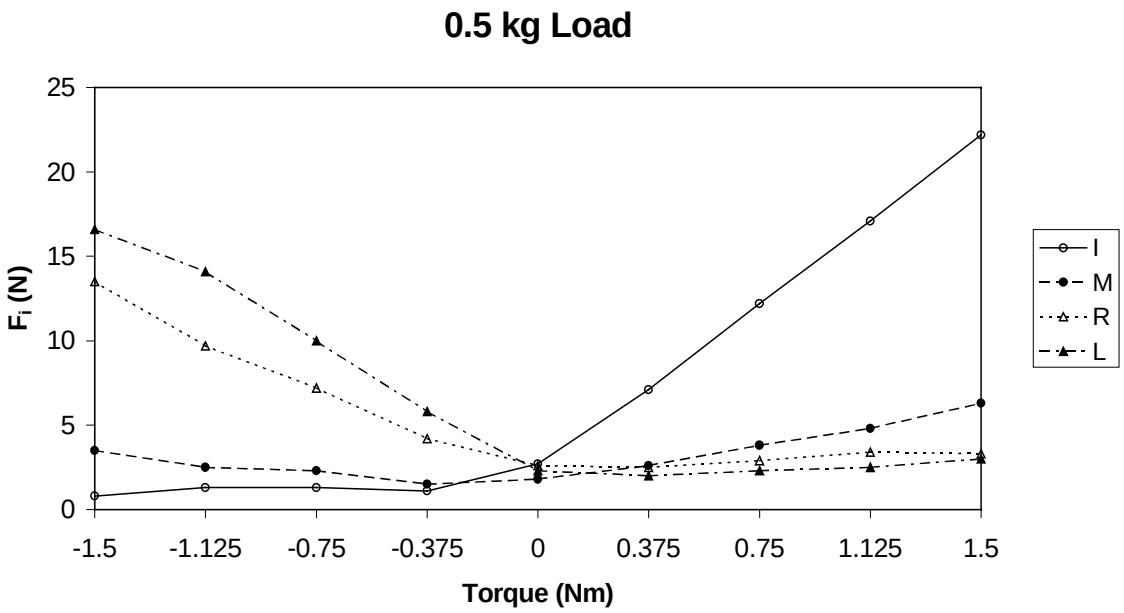
I, the undersigned, have defined and explained the studies involved to the above volunteer.

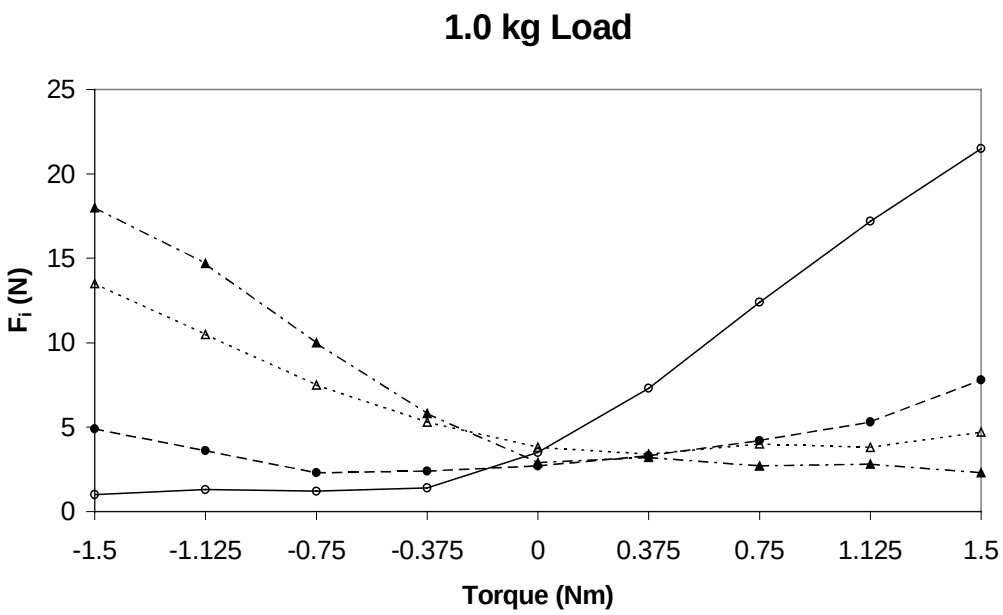
_____

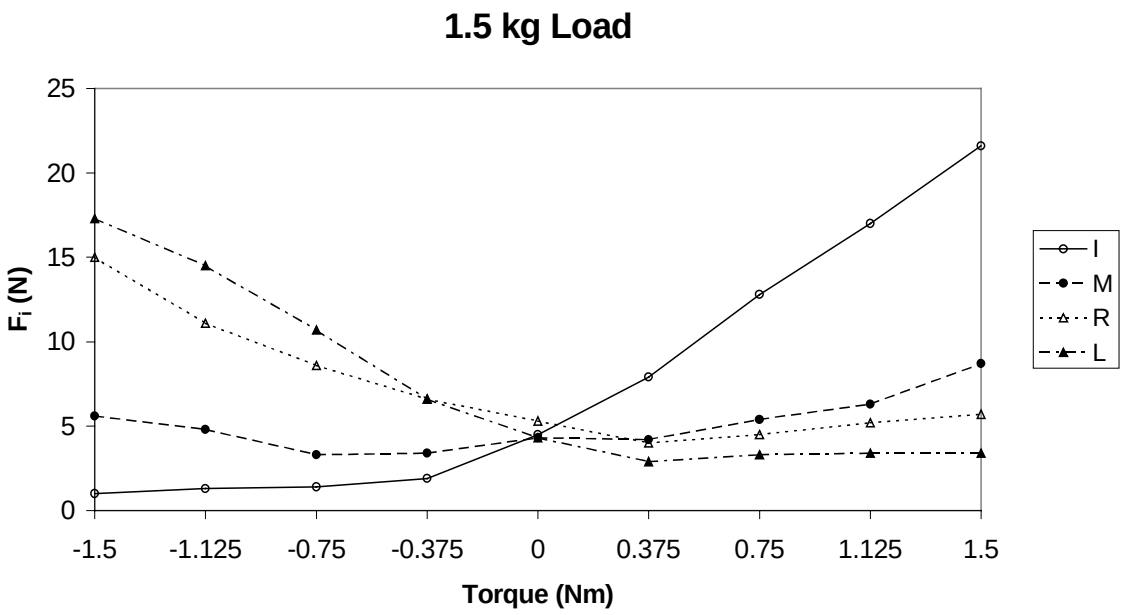
Volunteer Date

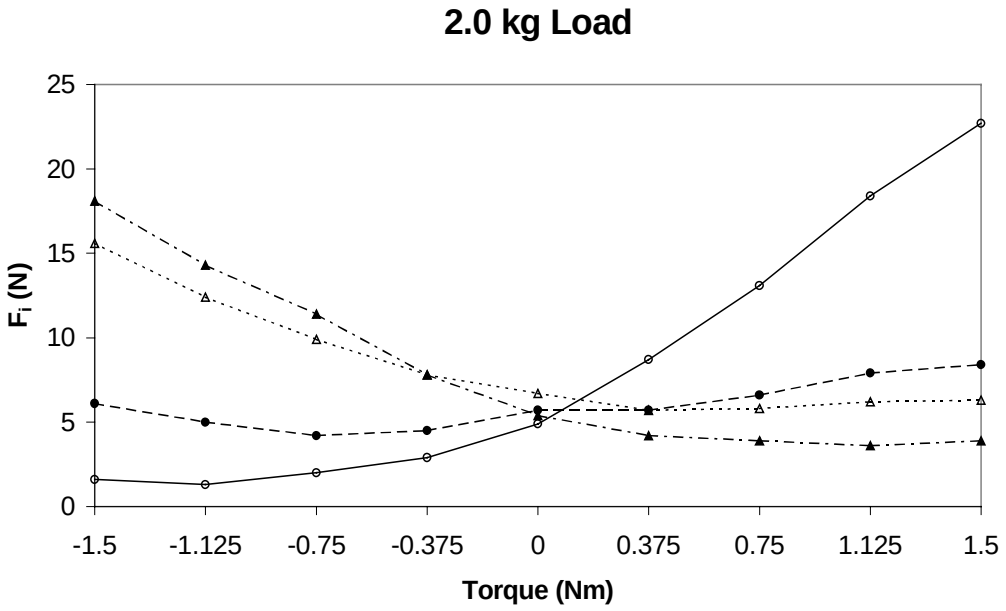
APPENDIX B

FINGER FORCE (F_i) DATA






1.5 kg Load
25
20
15
10
5
0
F_i (N)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L


2.0 kg Load
25
20
15
10
5
0
F_i (N)
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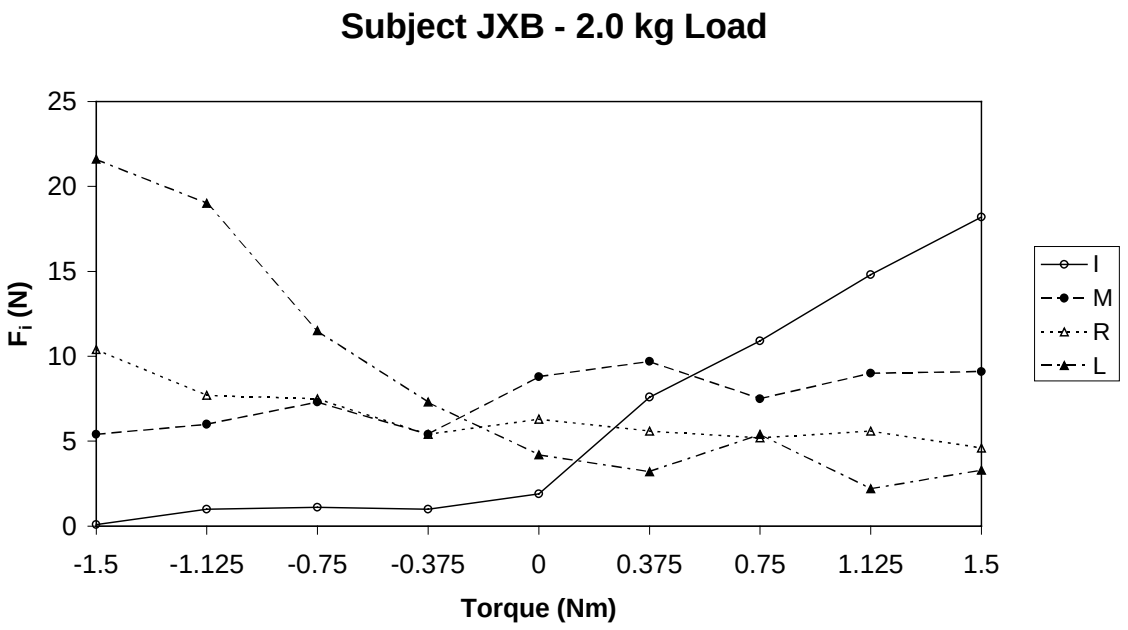
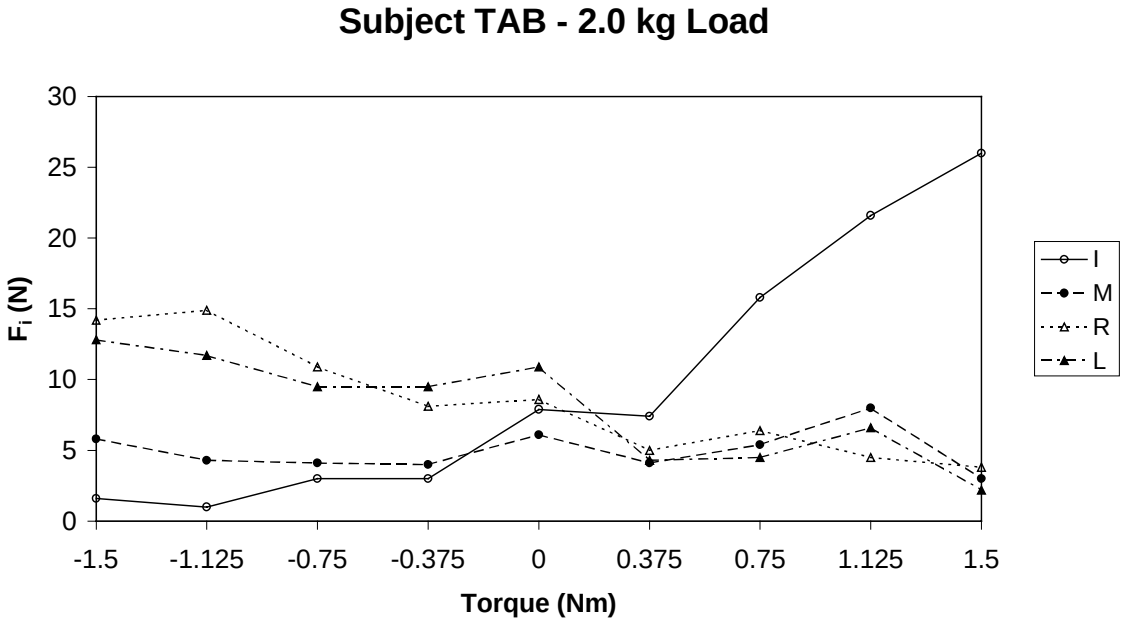
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)


Subject JXB - 2.0 kg Load
25
20
15
10
5
0
F_i (N)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L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25
20
15
10
5
0
F_i (N)
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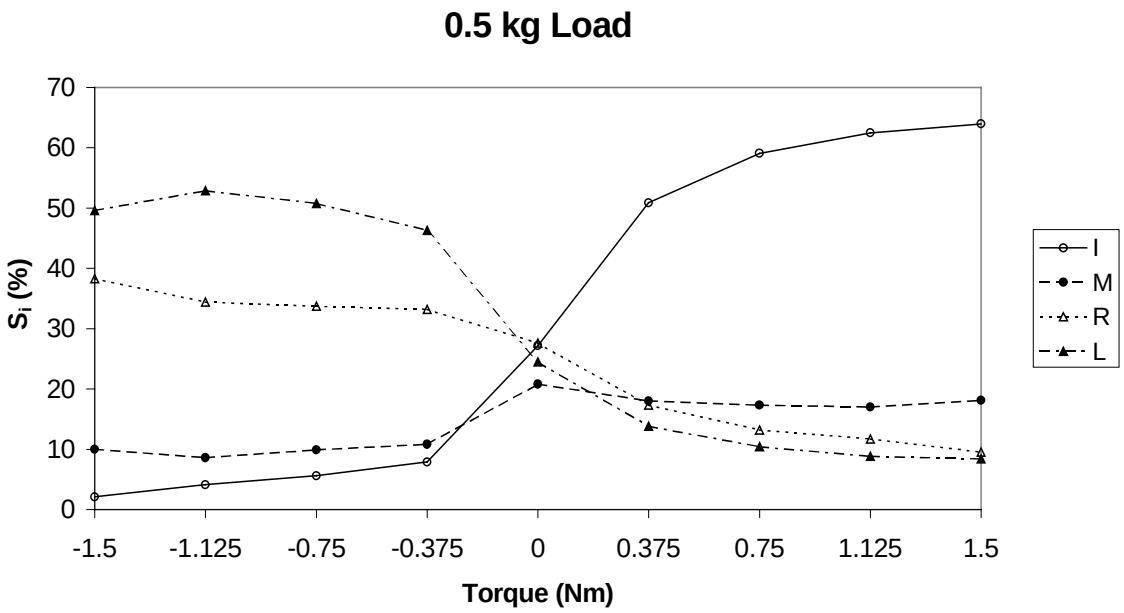
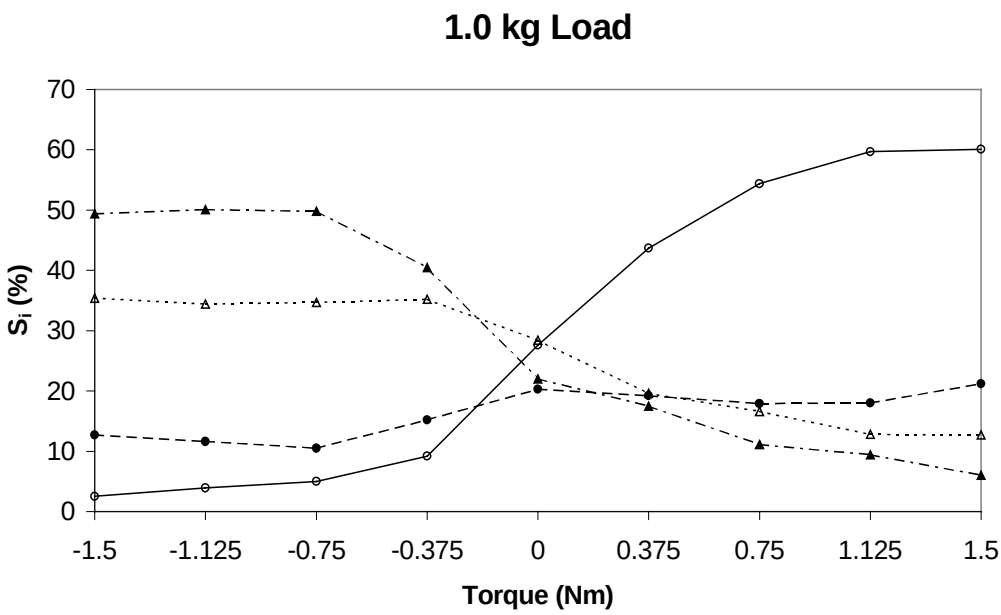
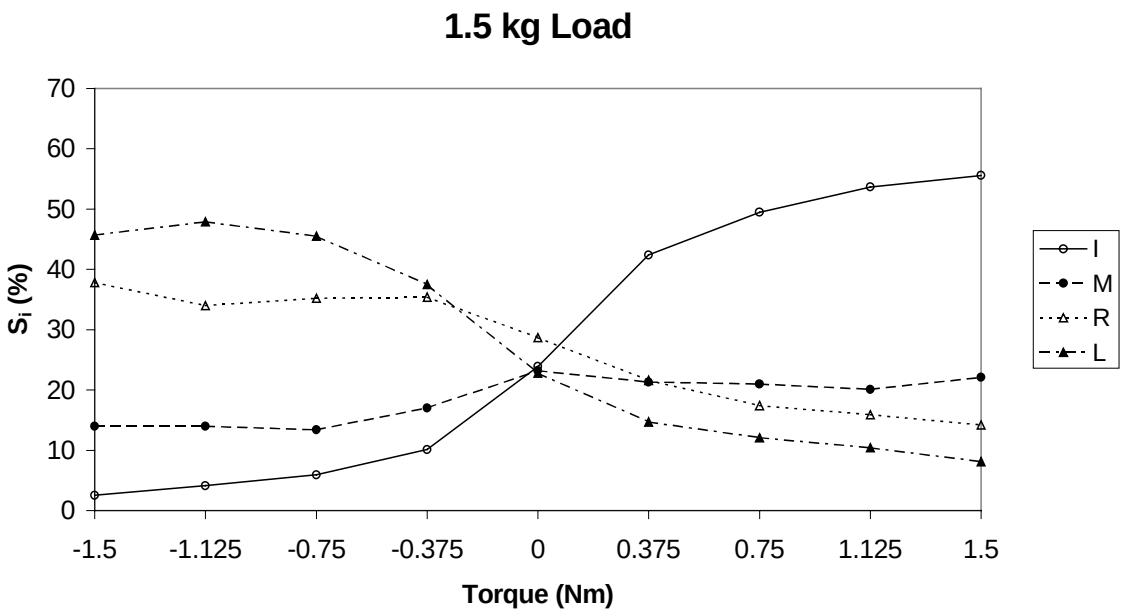
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

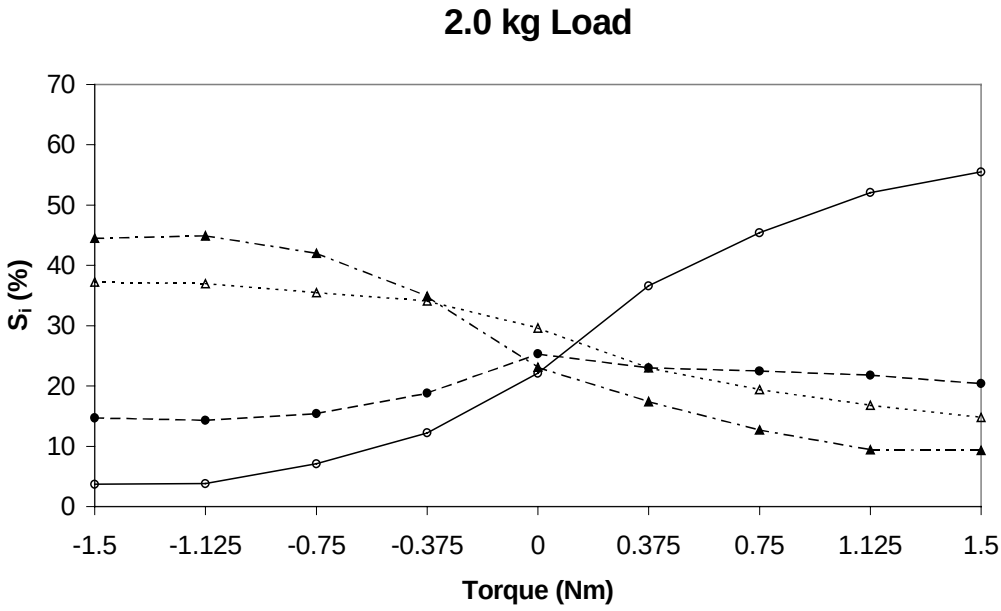
APPENDIX C

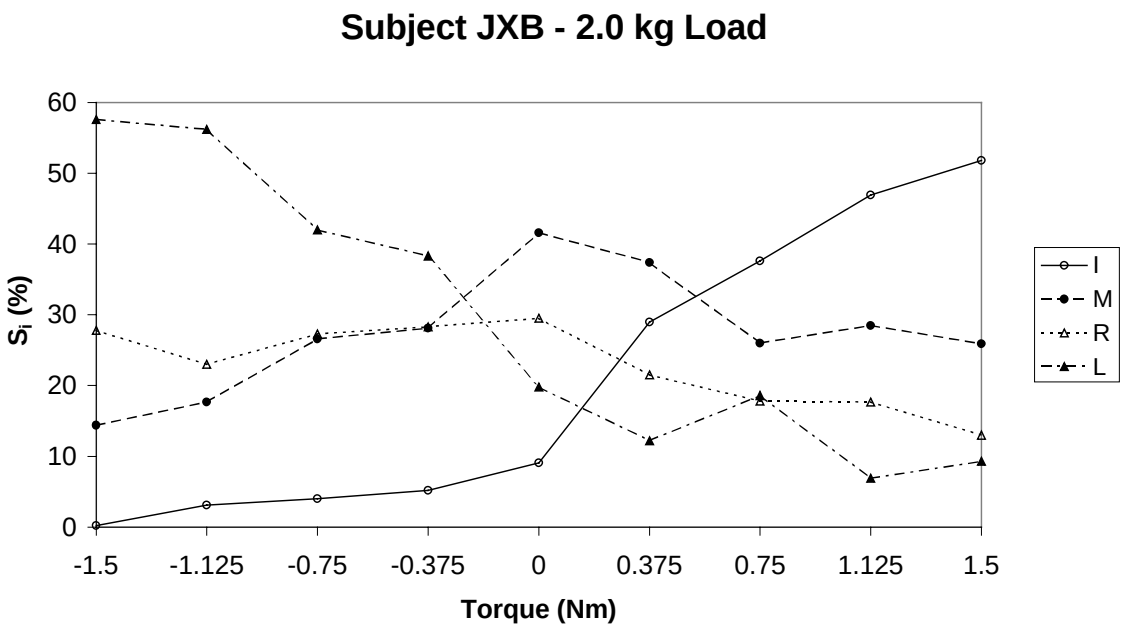
FORCE SHARING (S_i) DATA






1.5 kg Load
70
60
50
40
30
20
10
0
Si (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L


2.0 kg Load
70
60
50
40
30
20
10
0
Si (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)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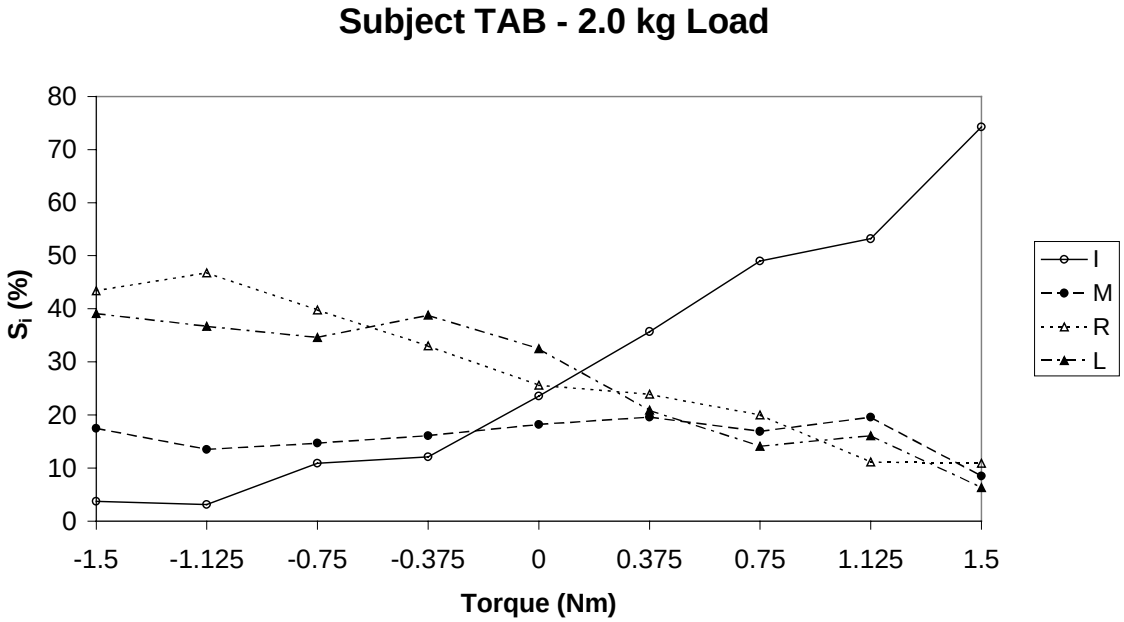
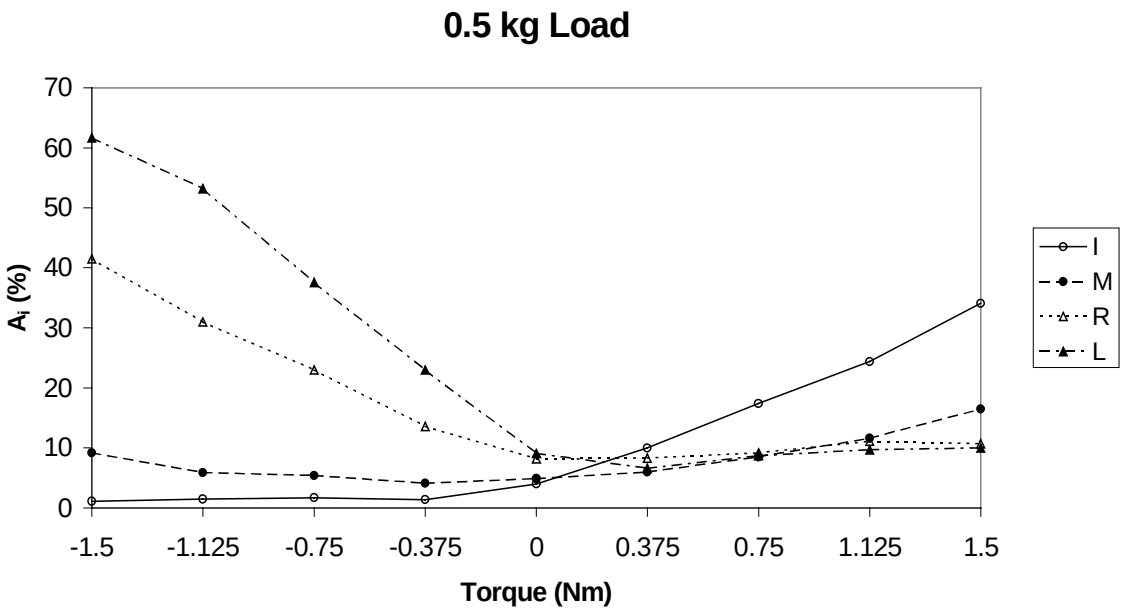
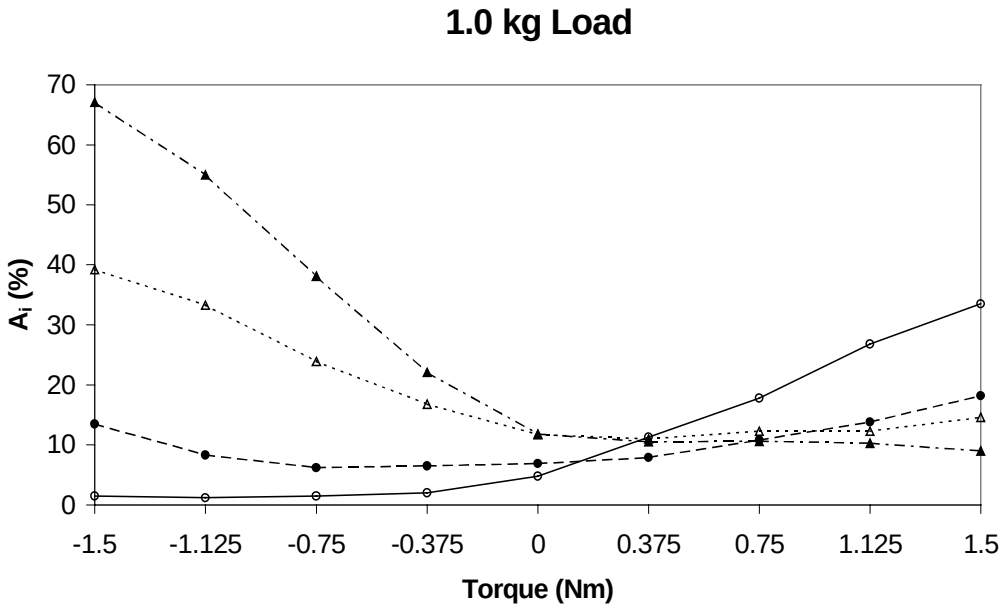
60
50
40
30
20
10
0
S_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

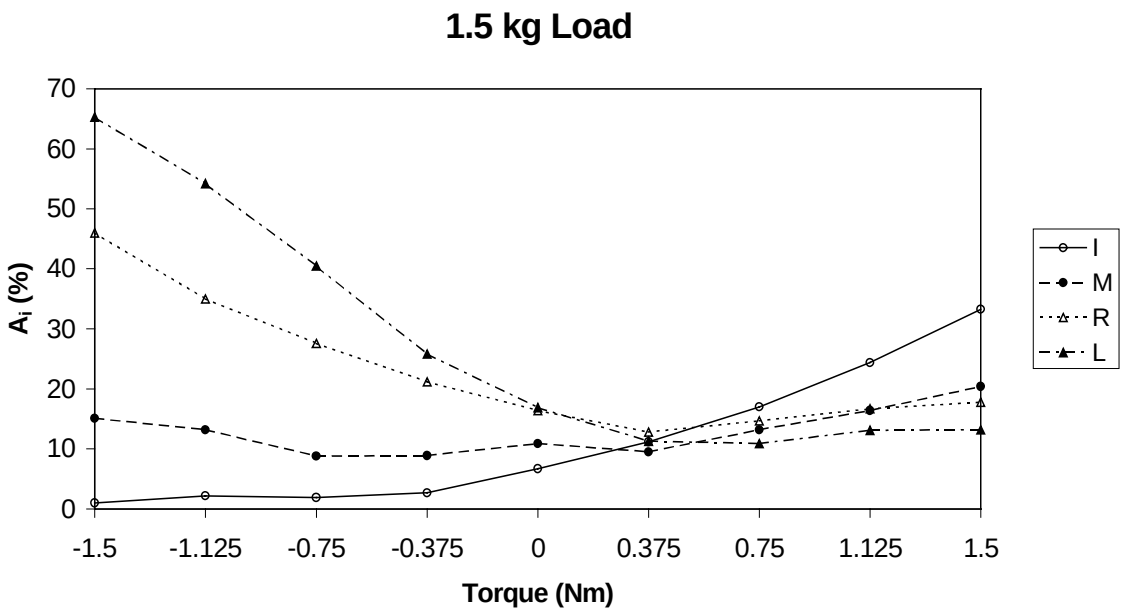

Subject TAB - 2.0 kg Load
80
70
60
50
40
30
20
10
0
S_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

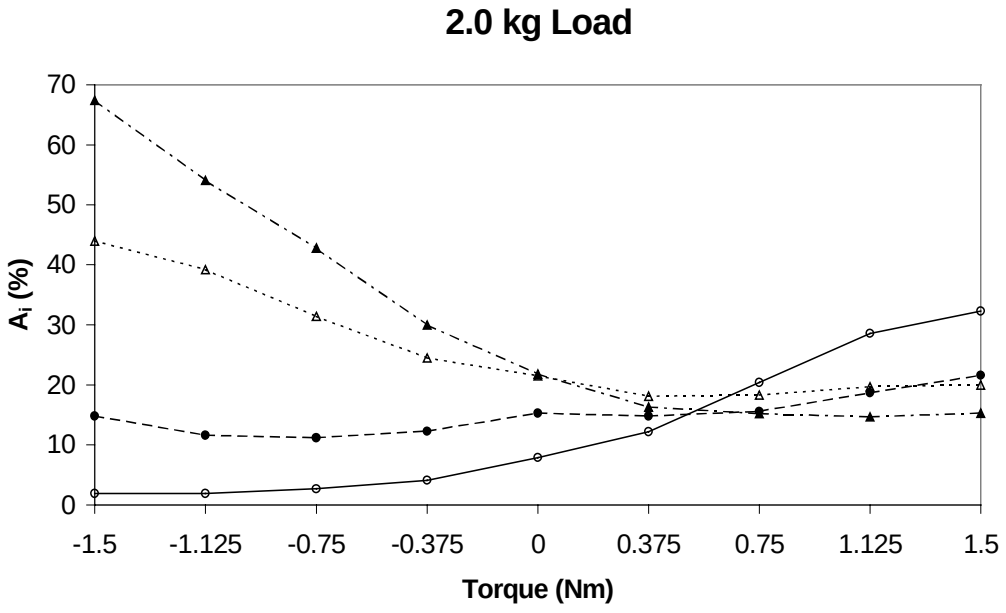
APPENDIX D

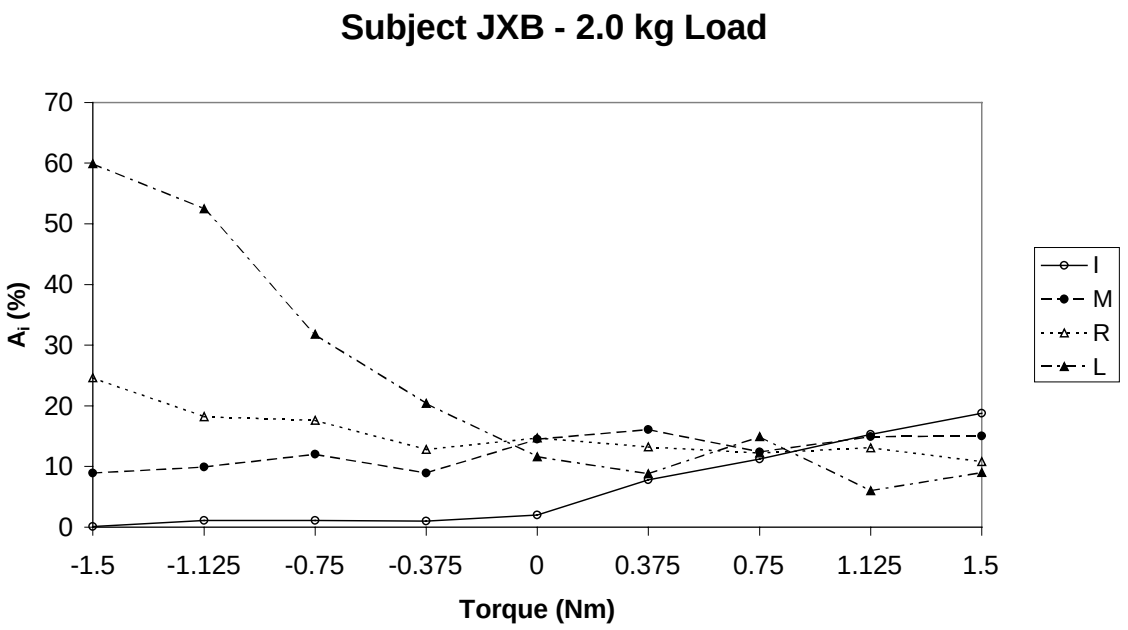
FORCE ACTUALIZATION ($A_{i/i}$) DATA

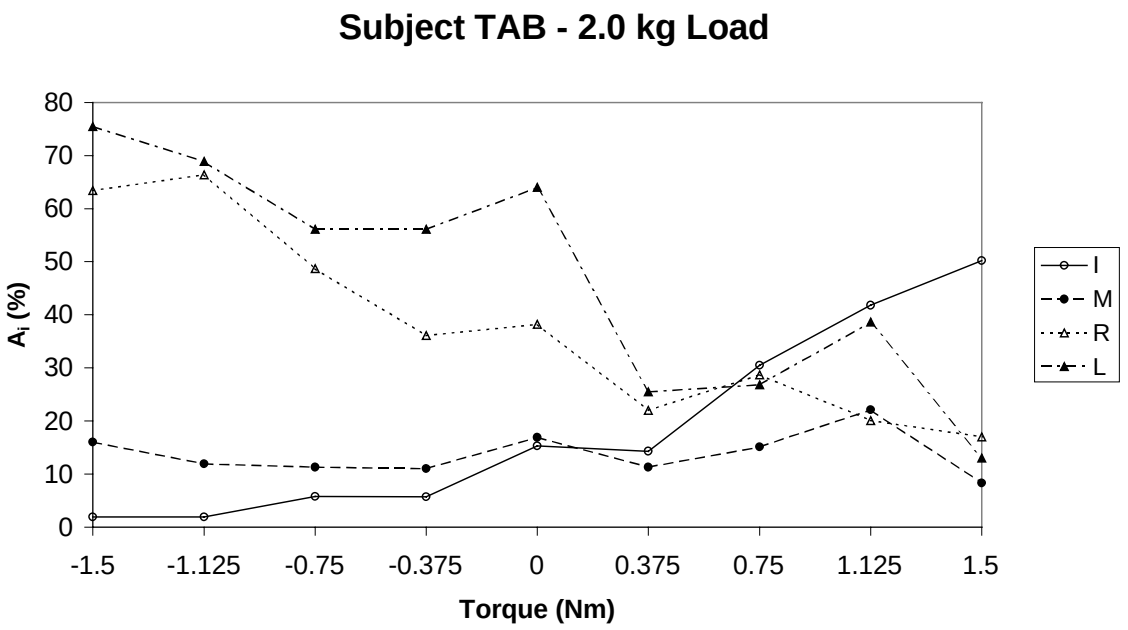





1.5 kg Load
70
60
50
40
30
20
10
0
A_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

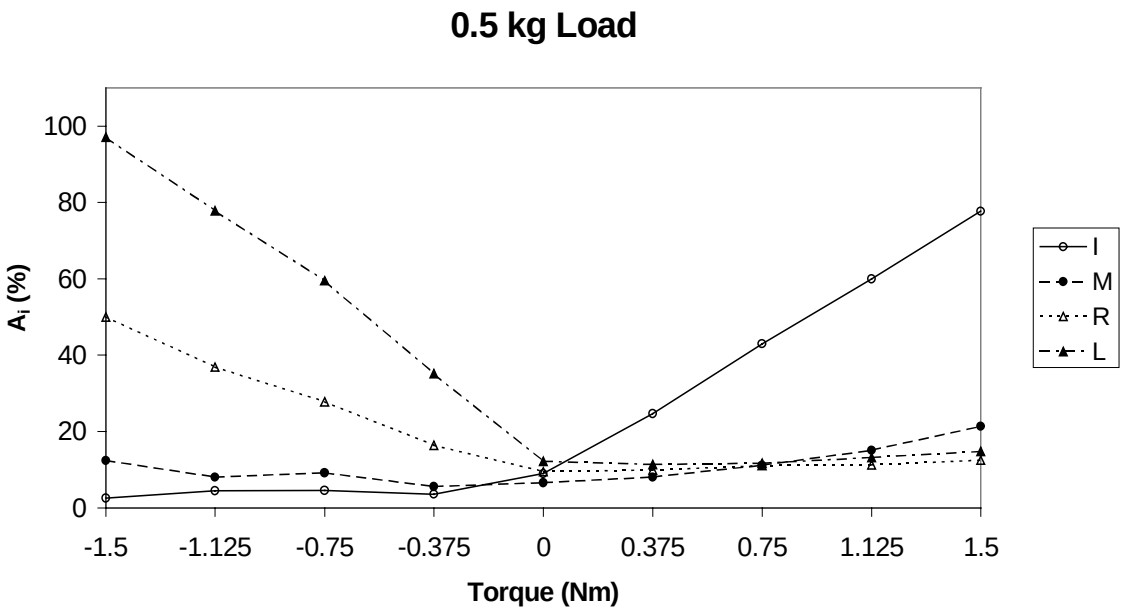

2.0 kg Load
70
60
50
40
30
20
10
0
A_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)

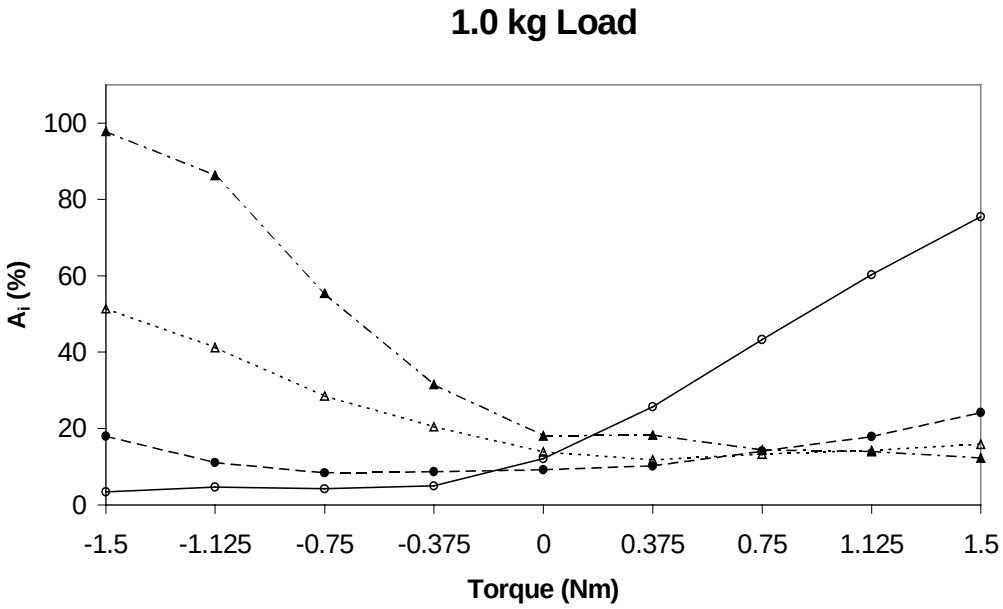

Subject JXB - 2.0 kg Load
70
60
50
40
30
20
10
0
A_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

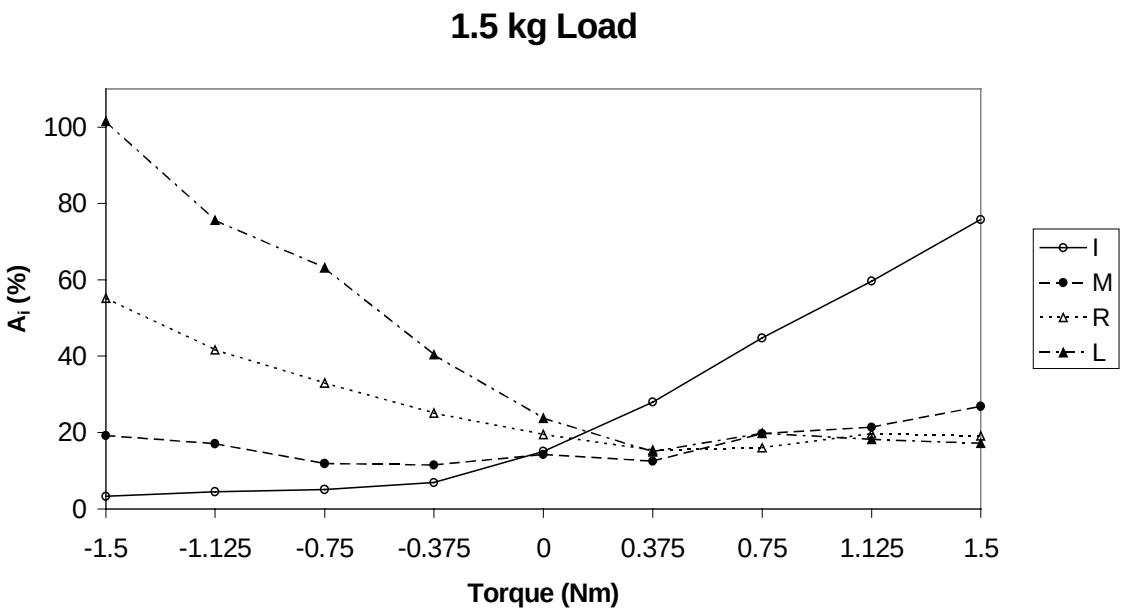

Subject TAB - 2.0 kg Load
80
70
60
50
40
30
20
10
0
A_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

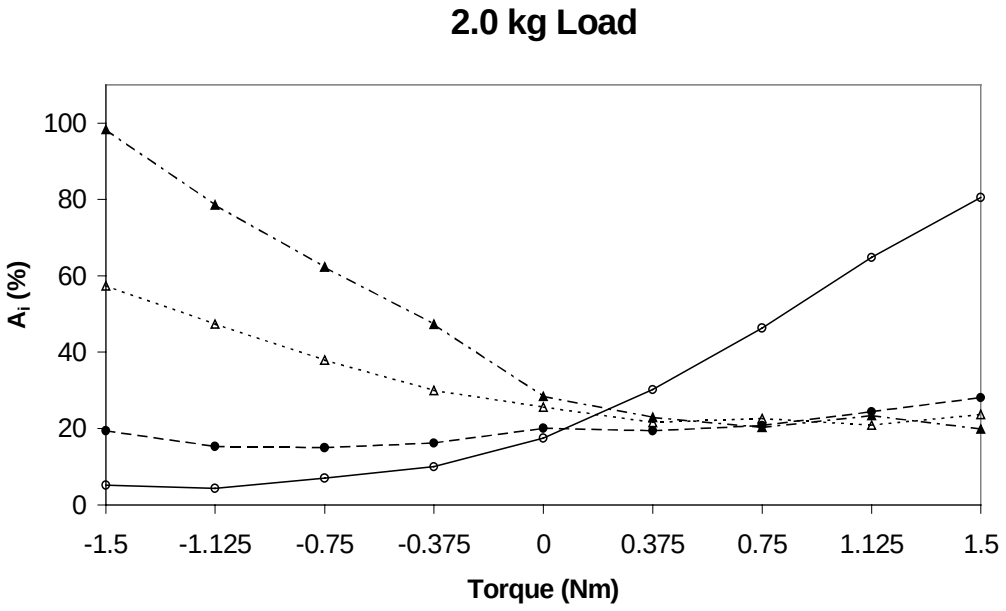
APPENDIX E

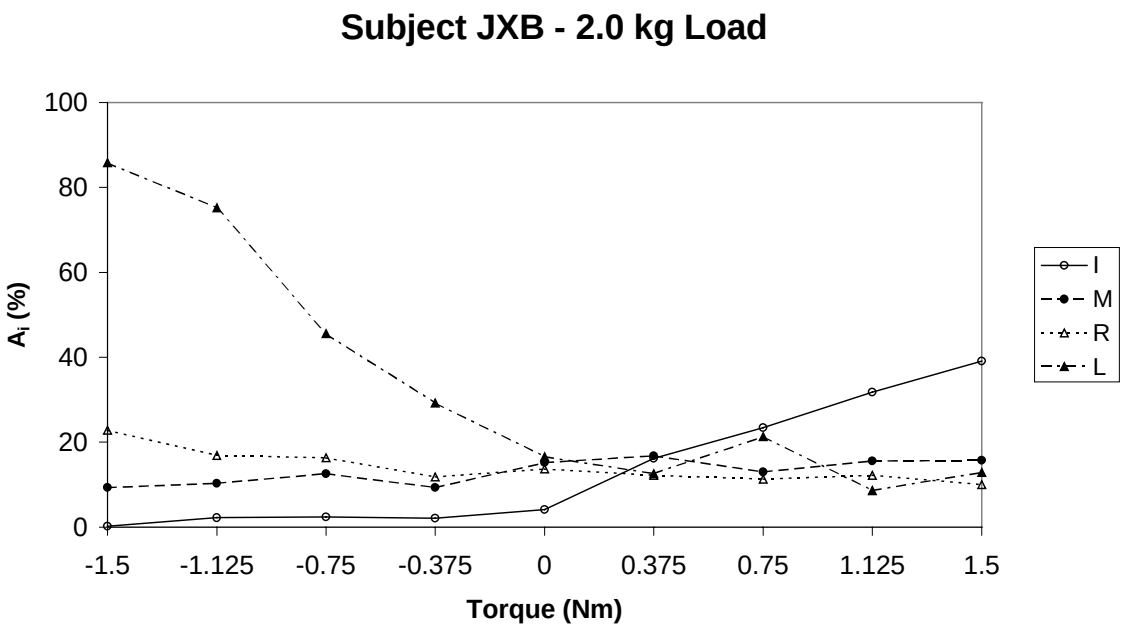
FORCE ACTUALIZATION ($A_{i/IMRL}$) DATA

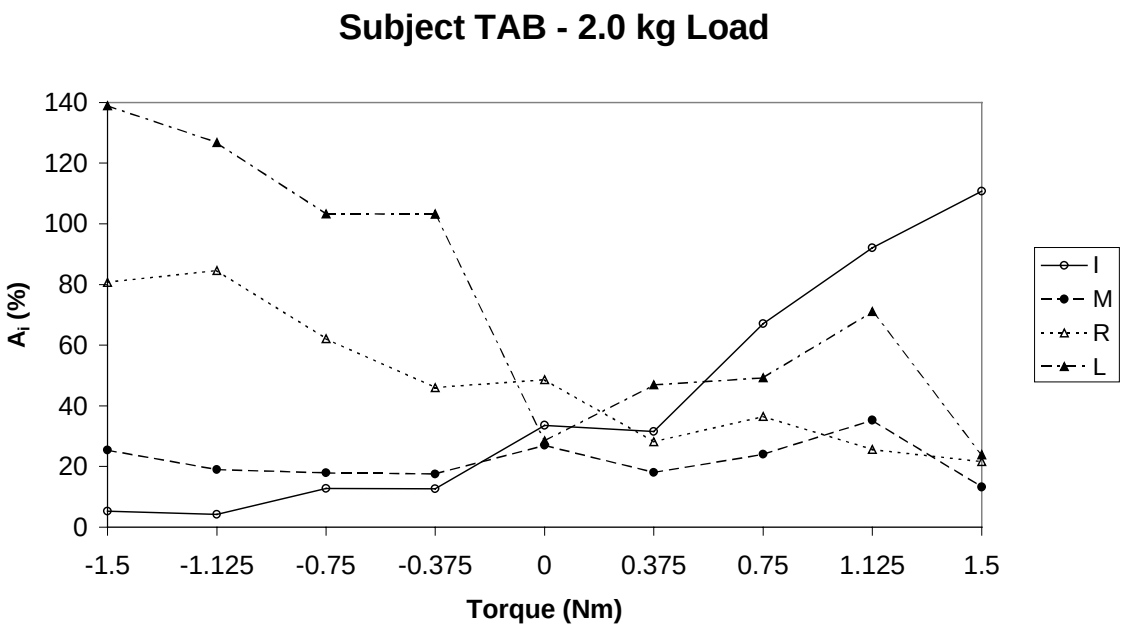





1.5 kg Load
100
80
60
40
20
0
A_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

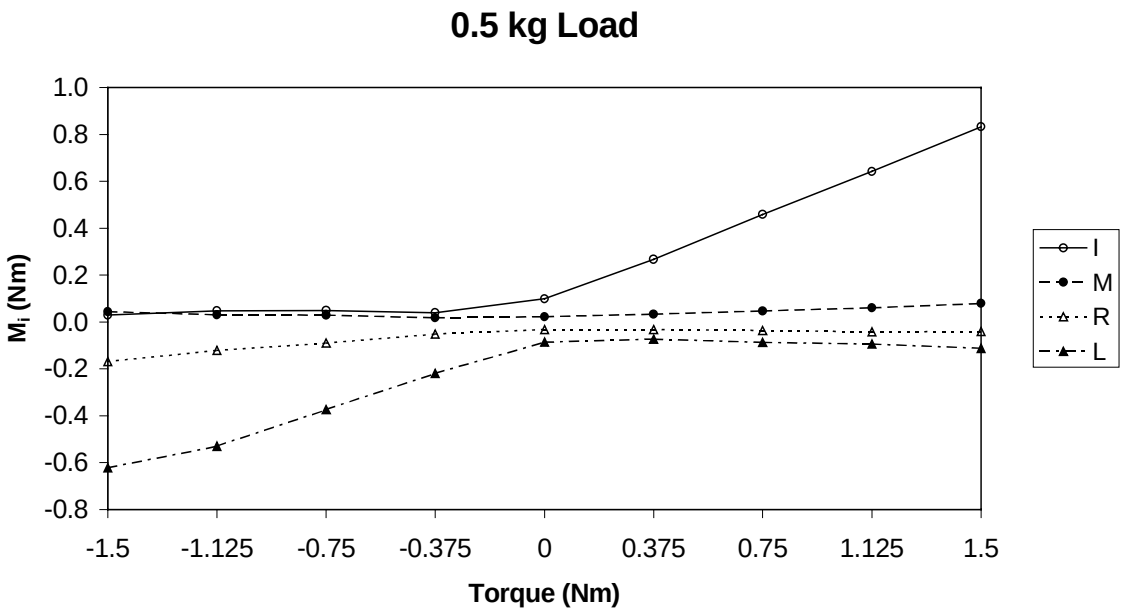

2.0 kg Load
100
80
60
40
20
0
A_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)

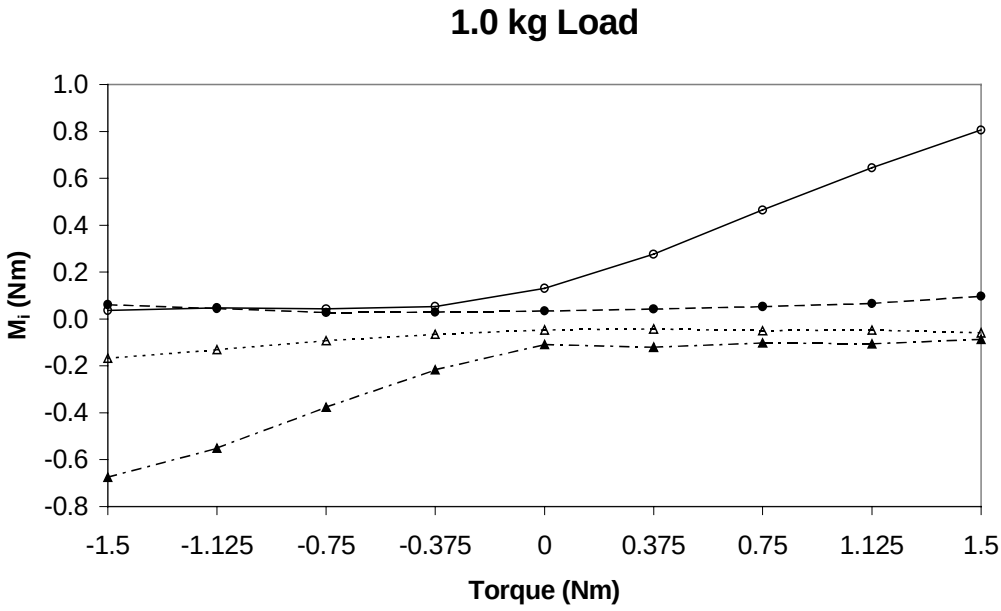

Subject JXB - 2.0 kg Load
100
80
60
40
20
0
A_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

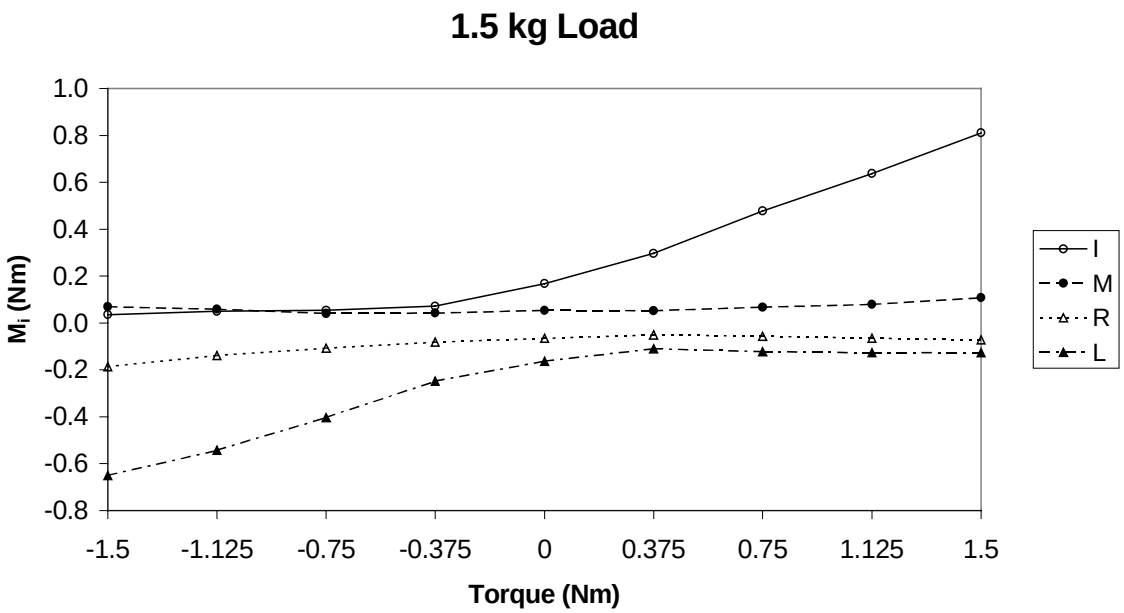

Subject TAB - 2.0 kg Load
140
120
100
80
60
40
20
0
A_i (%)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

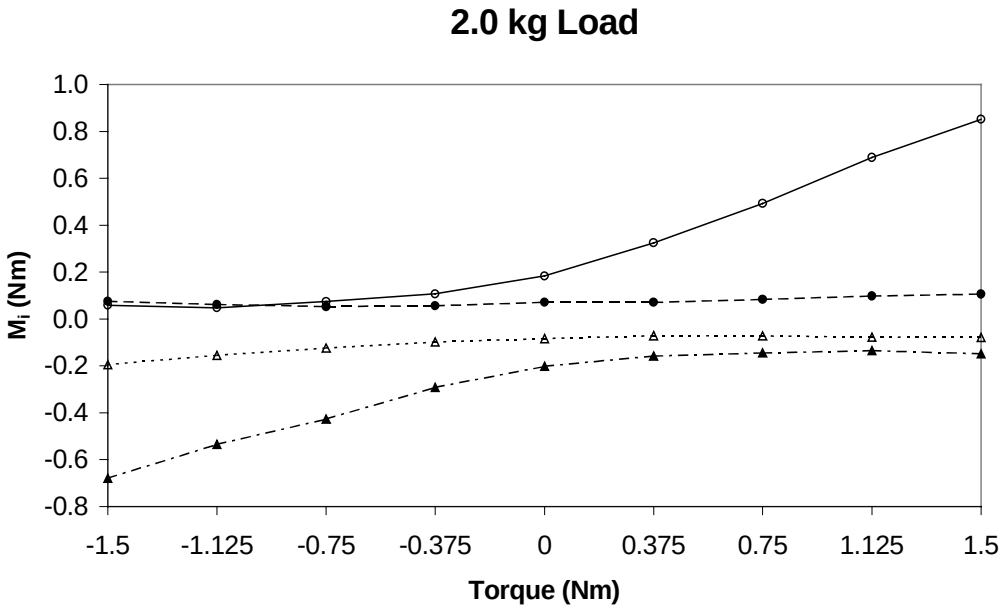
APPENDIX F

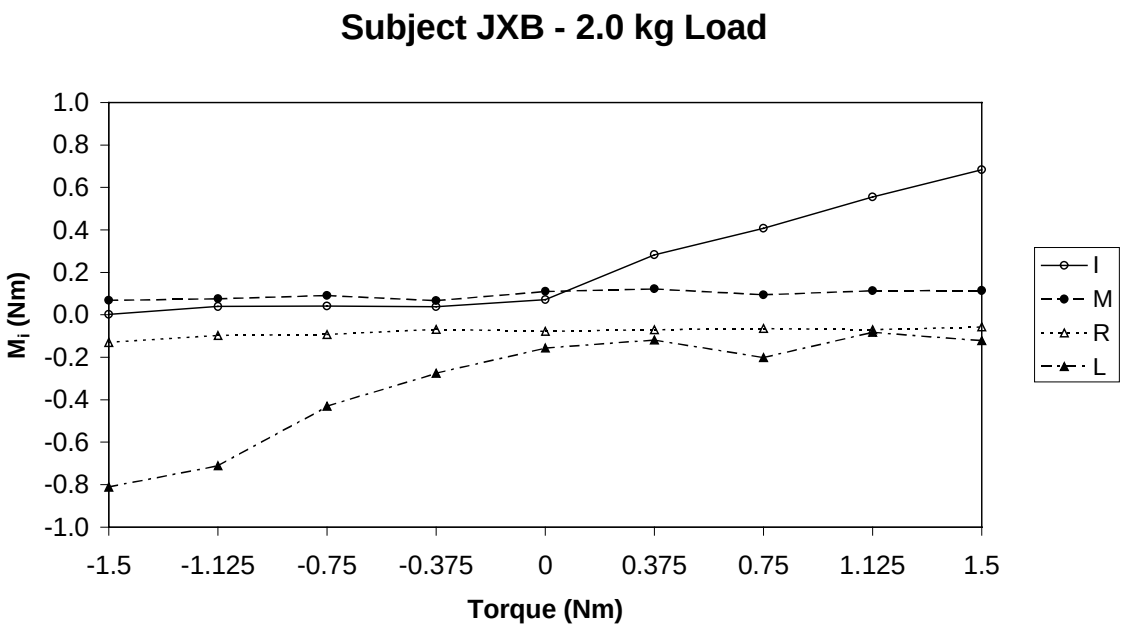
FINGER MOMENT (M_i) DATA

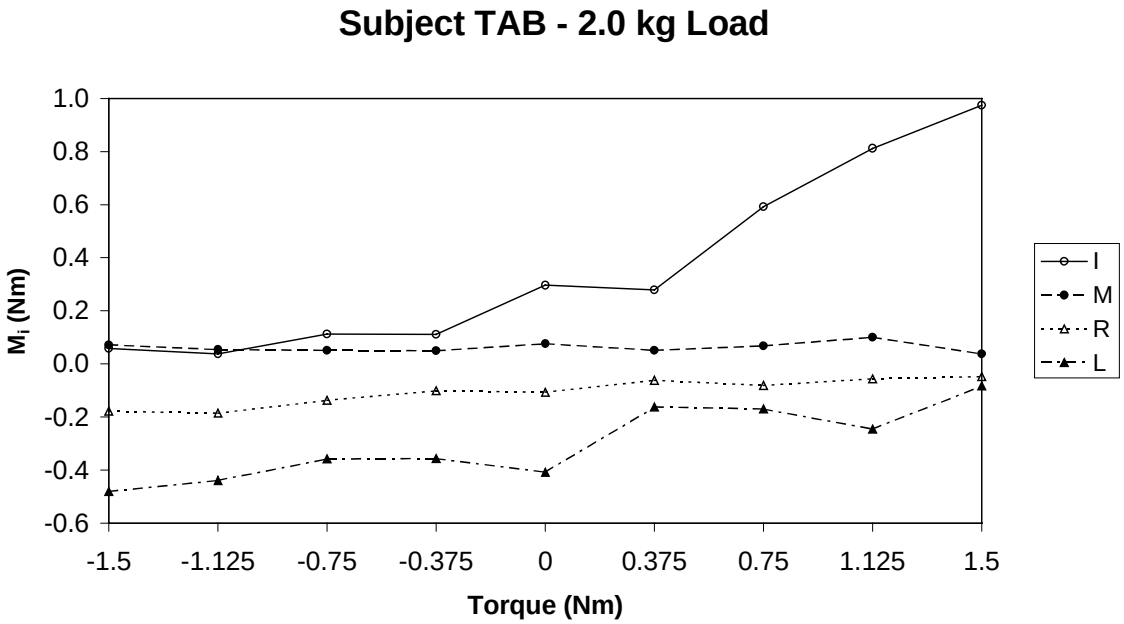





1.5 kg Load
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
M_i (Nm)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L


2.0 kg Load
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
M_i (Nm)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)


Subject JXB - 2.0 kg Load
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
M_i (Nm)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L


Subject TAB - 2.0 kg Load
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
M_i (Nm)
-1.5
-1.125
-0.75
-0.375
0
0.375
0.75
1.125
1.5
Torque (Nm)
I
M
R
L

VITA

EDUCATION:

Ph.D., Kinesiology, 2002, The Pennsylvania State University, University Park, PA
M.S., Special Studies: Biomechanics, 1994, St. Cloud State University, St. Cloud, MN
B.S., Pre-professional Studies, 1991, University of Notre Dame, Notre Dame, IN

PUBLICATIONS:

Rosenbaum, D.A., & Gregory, R.W. (2002). Development of a method for measuring movement-related effort: biomechanical considerations and implications for Fitts' law. *Experimental Brain Research*, 142, 365-373 .

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Gregory, R., & Zatsiorsky, V. (1998). Variability of total force versus individual finger forces in multifinger tasks. In *Proceedings of NACOB '98: The Third North American Congress on Biomechanics* (pp. 535-536). University of Waterloo, Waterloo, Ontario, Canada.

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