

ABSTRACT

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CONDITIONS AND SPEED ON FINGER
INTERDEPENDENCY

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The study investigated the contribution of peripheral and neurological factors during different movement and speed conditions in young adults in order to determine which factor played a greater role in finger interdependency. The results showed that finger interdependency was greater in voluntary than involuntary movement conditions and greater during the slower speed (0.25 Hz) condition. The proximity hypothesis was confirmed from our enslaving values. The study concluded that finger interdependency is larger during the voluntary movement condition, when both peripheral and neurological factors are involved in movement. A broader range of speeds should be explored to better understand its role in finger interdependency. Further studies are needed in order to expand on the current knowledge of the proximity hypothesis, especially in regards to its presence during the involuntary movement condition.

THE EFFECTS OF FINGER MOVEMENT CONDITIONS AND SPEED ON
FINGER INTERDEPENDENCY

By

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Chapter 1 - Introduction

Complete hand and finger independence is often assumed when considering manipulative movements. This would be a correct assumption if one were to examine the movements of a robotic hand, in which each finger has separate effectors. The fingers of the human hand, however, cannot move (Li, et al., 2004) or produce forces independent from one another (Hager-Ross and Schieber, 2000; Lang and Schieber, 2004). In fact, as a person voluntarily moves or produces force with one finger (task finger), the other fingers (non-task fingers) produce involuntary motions and various levels of force. This phenomenon, in which an involuntary force or motion is produced by non-task fingers, is called finger enslaving (Li, et al., 2004; Zatsiorsky, et al., 2000).

Enslaving has been used as an index for finger interdependency and attributed to peripheral and neurological factors (Hager-Ross and Schieber, 2000; Schieber and Santello, 2004). The peripheral factors include anatomical connections within the hand and forearm [e.g., web space soft tissue connecting fingers and the flexor digitorum profundus' insertion into multiple fingers (Hager-Ross & Schieber, 2000; Malerich et al., 1987)]. Neurological factors include interdependent finger control by the central nervous system (CNS) due to overlapping digit representation in the hand area of the primary motor cortex, the synchronous firing of cortical cells, and a common neuronal input to multiple muscles (Bremner, Baker and Stephens, 1991; Fetz and Cheney, 1980; Matsumaura et al., 1996; Schieber, 2001). These factors have been investigated during previous studies [i.e., isometric force pressing (i.e. “kinetic”) tasks (Li, et al., 2001; Zatsiorsky, et al., 2000) and kinematic finger movement tasks (Hager-Ross and Schieber, 2000; Lang and Schieber, 2004; Li et al., 2004)].

Finger interdependency is well documented, but only a few attempts have been made to quantify the peripheral and neurological factors involved in finger movement. Previous studies (Hager-Ross and Schieber, 2000, Zatsiorsky, 2000, Li, et al, 2004) attempted to explain factors of finger interdependency but did not test during involuntary (i.e. “passive”) conditions. As such, the data was only representative of voluntary (i.e. “active”) conditions. Other investigators have attempted to quantify the contributions of involuntary mechanical properties and voluntary neuromuscular control by investigating the involuntary and voluntary movements of fingers. Lang and Schieber (2004) studied motion enslaving by measuring kinematic (angular) input from the task finger and recording the kinematic output from the non-task fingers. The middle, ring and little fingers exhibited greater movement independence during the voluntary condition while exhibiting less movement independence during the involuntary condition, indicating that mechanical coupling was a large factor in finger independence. However, though the fingers were tested in both involuntary and voluntary movement conditions and were connected to an electromyographic (EMG) recording device, the subjects were not instructed to completely relax the non-task fingers during the voluntary condition, suggesting that various muscles, not monitored by the EMG machine, may have been activated to hold the other fingers in position. Thus, when the task finger flexed, the non-task fingers may have contracted extensor muscles to avoid flexion. Determining the contributions of voluntary versus involuntary control may not have been accurate in this condition.

Moreover, in this type of experimental setup, angular displacement could not be induced in the involuntary movement because in the relaxed position, joints would touch and therefore distort the angle displacement that would occur in the non-task fingers.

Instrumented gloves were used to measure angular displacement, but these may have served as an external source of passive coupling. The results from previous studies may have overestimated the passive coupling that actually occurred between fingers.

Schieber and Santello (2004) also found similar issues with co-contraction, such that it occurred in extrinsic and intrinsic hand muscles during experiments involving single fingertip force production. Furthermore, kinetic input from the task finger in voluntary movement would allow for kinetic output from the non-task fingers to be attained, but it would be difficult to induce force on the task fingers while in an involuntary movement condition. Similarly, an approach utilizing kinetic input from the task finger in voluntary movement would allow for kinematic output to be measured in the non-task fingers; however, during involuntary movement, force could not be induced to the task finger without engaging it in some type of movement involving CNS control.

Obtaining both voluntary and involuntary actions of the task finger kinematically (with the assistance of a lever to aid the task finger during involuntary movement) while kinetically recording the non-task fingers' output responses would provide valid quantifiable data on the role of central and peripheral factors in finger interdependency. This approach has not yet been used to examine these factors, and will be employed in the current study.

The peripheral and central factors previously stated are primary reasons for the enslaving effects seen that result in inter-digit dependency. Two other areas of interest will be explored. Hager-Ross and Schieber (2000) found that increases in task finger speed (2 Hz to 3 Hz) reduced task finger independence. They hypothesized that in order to cover distances at higher speeds, velocities must be increased. The fingers' biomechanical constraints cause the non-task fingers to be pulled along at a greater rate during higher

speeds. This combination of higher viscoelastic coupling between the fingers as well as greater functional activation in the M1 (Rao, et al., 1996) may have reduced finger independence. By choosing a slower overall range of speeds than in previous studies, this study will further investigate effects of speed on finger interdependence.

Previous studies on finger flexion tasks showed that finger enslaving was greater in non-task fingers closer to the task finger, known as the “proximity” hypothesis (Zatsiorsky, Li and Latash, 1998; Zatsiorsky, Li and Latash, 2000). It has been confirmed in many of the previous studies exploring finger manipulation (Zatsiorsky, Li and Latash, 2000; Li et al., 2004; Kim, et al., 2008; Oliveira et al., 2008). The study is designed to test the proximity hypothesis using a calculation similar to that used in another study (Oliveira, et al., 2008), but apply it to average enslaving values, and not maximal voluntary force values.

Therefore, the purpose of this study is to examine the effects of changing movement and speed conditions in the fingers of young adults to quantify and differentiate the contribution of peripheral (i.e. biomechanical) and neurological (i.e. CNS) factors. Quantification of both factors will allow the current study to make inferences about which factor plays a greater role in finger interdependency.

The thesis is divided into five chapters. The first chapter introduced the research aims and provided the rationale behind the study. The second chapter discusses finger interdependency and the constraints affecting hand manipulation. The third chapter describes and explains the methods used during the study. Chapter four presents the results of the study and a discussion on the variables investigated. Finally, a conclusion chapter is presented with limitations and recommendations for future study.

General Aim

The purpose of the study was to investigate the effects of different movement and speed conditions on finger interdependency through quantification and differentiation of the peripheral and central factors affecting finger interdependency during those conditions.

Specific Aims

- To evaluate finger interdependency during voluntary and involuntary movements.
- To verify if finger interdependency will be greater during movements of higher speed (0.5 Hz) than lower speed (0.25 Hz).
- To test and confirm the proximity hypothesis.

Hypothesis

Hypothesis 1: Finger interdependency between fingers will be higher during voluntary than involuntary movements due to the involvement of both peripheral and central factors in voluntary movements.

Hypothesis 2: Finger interdependency will be greater during movements of higher speed (0.5 Hz) than lower speed (0.25 Hz) due to greater passive viscoelastic coupling between task and non-task fingers.

Hypothesis 3: Finger interdependency will decrease across fingers due to the non-task fingers' proximity relative to the task finger, also called the proximity hypothesis.

Chapter 2 – Review of Literature

Structural Description of the Hand

The hand, wrist and forearm are complex in structure, with a total of 27 bones. There are 14 phalangeal bones in the digits, five metacarpal bones in the palm, and eight carpal bones in the wrist (Drake, Vogl, and Mitchell, 2005). Four joint groups are composed from these bones: the distal interphalangeal (DIP), proximal interphalangeal (PIP), metacarpophalangeal (MCP), and carpometacarpal (CMC) joints (Figure 2.1). The DIP, PIP, and MCP joints are formed within the digits, between the distal, middle and proximal phalanges respectively. The lone exception is the thumb, which excludes the medial phalanx. The DIP and PIP joints have a hinge structure, which allows direction along one axis. The MCP joints are condyloid joints, which allow biaxial movement, both flexion-extension and abduction-adduction.

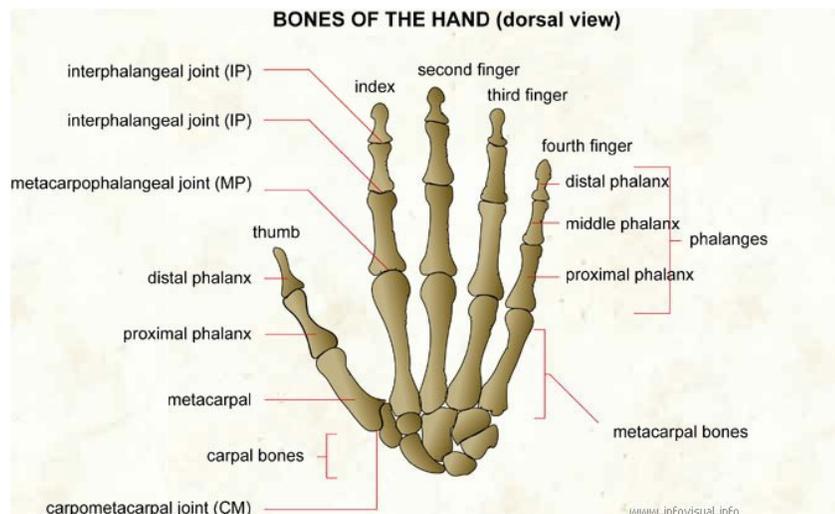


Figure 2.1 – Dorsal view of the bones and articulations of the hand (www.infovisual.info)

Carpal bones, tightly bonded by interosseous ligaments, comprise the wrist and are named after geometric shapes: the distal row consists of the trapezium, trapezoid, capitate, and hamate, while the proximal row consists of the scaphoid, lunate, triquetrum, and pisiform (Figure 2.2). The articulations, or joints, between bones are classified as intercarpal joints, and the articulation between the proximal and distal row is called the midcarpal joint. The intercarpal joints are gliding joints, allowing minimal side-to-side and back-and-forth movements (Drake, Vogl, and Mitchell, 2005).

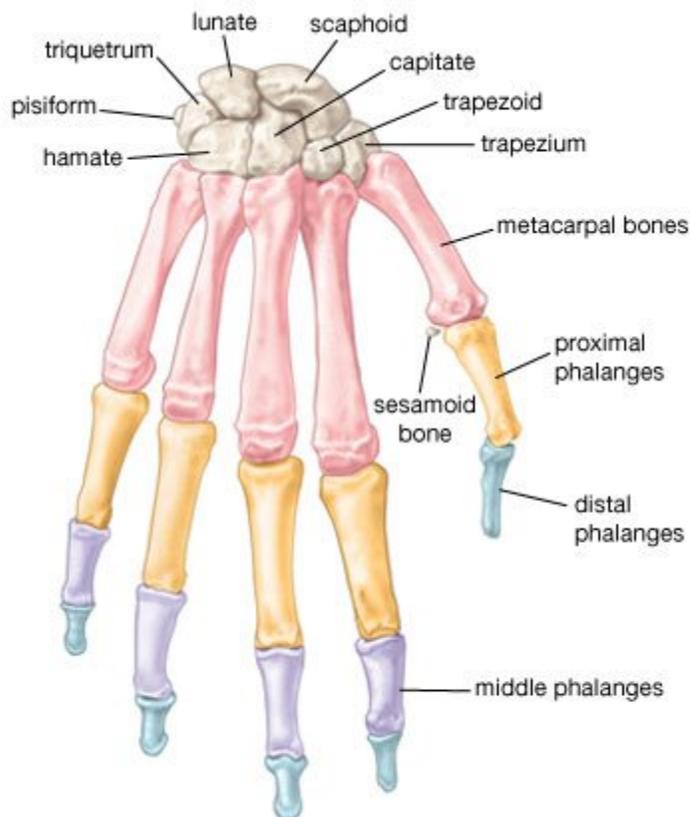


Figure 2.2 – Bones of the hand and wrist (Encyclopedia Britannica, Inc., 2008)

The joints provide a range of motion (ROM) of $60^{\circ} - 70^{\circ}$ in DIP joint flexion and $100^{\circ} - 110^{\circ}$ PIP joint flexion. In the MCP joint, the ROM for joint flexion varies from finger

to finger, with the pinky showing the largest ROM in flexion at 95°, and the index finger the smallest at 70°. The ROM at joint extension, according to Steindler's study of the human body (Shim, 2005), is approximately 20° - 30°. Abduction-adduction ROM is between 45° - 60°, with the index and little finger having a greater ROM than the ring and middle finger. In a flexion-extension position, the ROM decreases if there is a deviation in the abduction-adduction position and increases if there is not a deviation, due to the structure of the metacarpal. The CMC joint is immobile due to the strength of the interosseous ligaments.

The complexity of the hand does not stop at its skeletal structure, but includes the musculature of the hand surrounding it. The muscles that cause movement in the fingers can be classified by the origin of the muscles. Extrinsic muscles of the forearm are larger and related to the strength of the hand, while the intrinsic muscles of the hand contribute to the finer movements of the hand (Freivalds, 2004; Shim, 2005). The extrinsic muscles can be divided into anterior and posterior subgroups, with the anterior muscles acting as the flexors of the hand and the posterior acting as the extensors (Figure 2.3). Main flexor muscles include the flexor digitorum profundus (FDP), which is connected to the distal phalanges (Figure 2.4) and the flexor digitorum superficialis (FDS), which is connected to the medial phalanges (Figure 2.5). The FDS is utilized when more force is needed, such as during maximal voluntary contraction (MVC). The FDP is divided into two parts, radial and ulnar; the radial part connects to the index finger (at the distal phalange) while the ulnar part connects to the middle, ring, and little fingers. The radial part's connection solely to the index finger consequently gives it the most independence in movement (Li, et al., 2004). The intrinsic muscles are divided into three groups: the thenar, which allows thumb flexion/extension and ab/adduction, the hypothenar, which is responsible for little finger

flexion and adduction, and midpalmar, which allows MCP flexion and ab/adduction of all fingers as well as the thumb. Supination in the hand is caused by the supinator muscle working synergistically with the biceps brachii, while pronation of the hand is caused by the pronator teres and pronator quadratus (Drake, Vogl, and Mitchell, 2005).

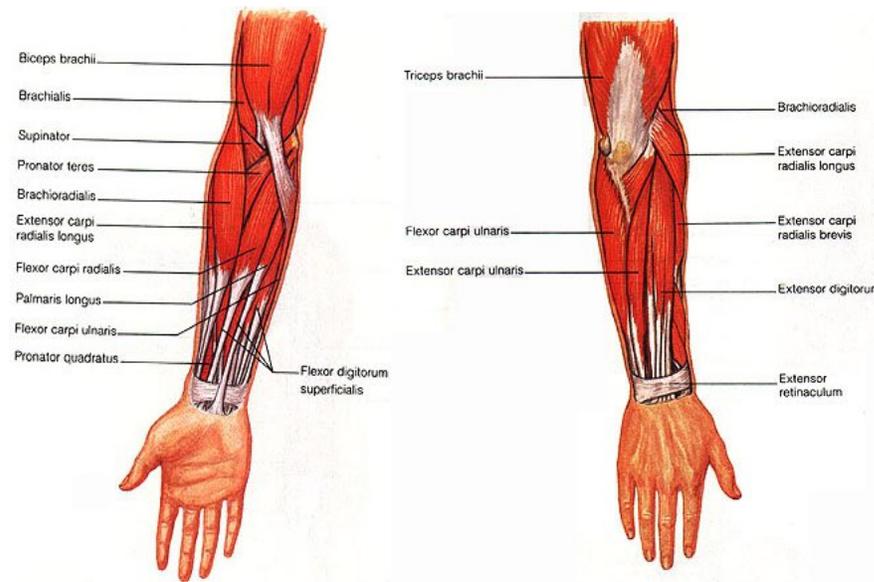


Figure 2.3 – Muscles of the forearm, anterior and posterior view (www.physioweb.org)

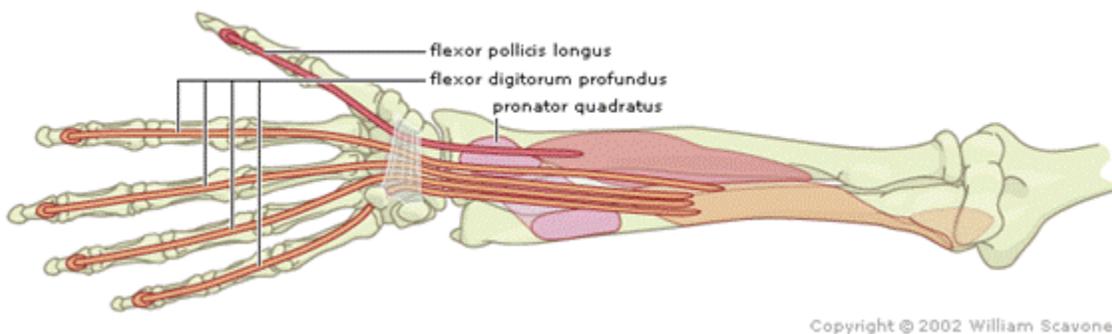


Figure 2.4 - Anterior view of the tendons of the forearm and hand (Scavone, 2002)

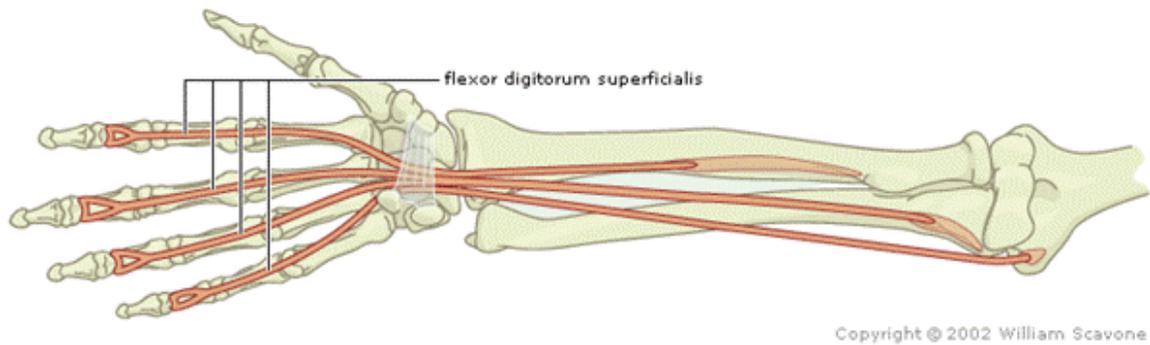


Figure 2.5 – Anterior view of the flexor digitorum superficialis tendon (Scavone, 2002)

Functional Description of the Hand

The complexity of the human hand is not without reason: the function of the hand is complex and skillful. Generally speaking, hand and digit (index (I), middle (M), ring (R), and little (L) fingers as well as the thumb) use can be broad and specific. Grasping requires a simultaneous motion of all the digits in a coordinated fashion around a certain object. Finer movements, such as playing a key on the piano, or typing letters on a keyboard, require more individuated movements from fingers. However, even in these situations, fingers still tend to move together (Schieber and Santello, 2004). Although increased finger independency is considered to be desirable for skillful hand manipulation, it has been documented that humans are not capable of independent control of individual fingers. Humans can neither move a single finger without changing the positions of the others (Hager-Ross and Schieber, 2000; Li et al., 2004; Schieber and Santello, 2004) nor produce one finger force without producing forces with the other fingers (Zatsiorsky, Li, Latash, 1998; Reilly & Hammond, 2000). This involuntary movement or force production by non-task fingers produces enslaving effects on the task finger.

The enslaving effects and consequent finger interdependence have been attributed to two constraining factors: peripheral and central constraints. In involuntary (passive) movements, the architecture of the hand and forearm mechanically couples fingers, resulting in enslaving and finger interdependency. The soft tissues of the web spaces (i.e. skin) cause finger interdependence among adjacent digits (Hager-Ross and Schieber, 2000; Schieber and Santello, 2004). Also, the extrinsic hand muscles FDP and FDS are connected to multiple tendons within the fingers (Figure 2.4 and 2.5). These multitendinous connections to extrinsic muscle can result in movement of non-task fingers during involuntary flexion of task fingers (Leijnse, 1997). Interconnected tendons of certain muscles, such as the juncturae tendinum, which connects the extensor digitorum communis (EDC) to different fingers, can also contribute to finger interdependency (Schieber and Santello, 2004). Anomalous other interconnections can also play a role in the mechanical coupling of adjacent fingers, such as the tendinous band between flexor pollicis longus and the FDP portion in the index finger (Hager-Ross and Schieber, 2000). Stretch reflexes activated during high frequency, large-arc movements from the spinal column, without central nervous intervention, can also cause finger interdependency.

Finger interdependence can also be attributed to poor CNS control during voluntary (active) movements. Whereas previous models such as Penfield's homunculus model and Woolsey's simusculus model suggested that certain portions of the primary motor cortex (M1) controlled specific fingers, recent studies showed broad M1 stimulation as finger movements occurred. The cortical cells of the brain can send signals to motoneurons, which can innervate muscle fibers of particular fingers. However, divergence of the signal can occur when a single neuronal input from the M1 is sent to two different interneuron pools

and muscles, which can result in synchronous finger movements (Schieber and Santello, 2004). Also, when finger movements are made, M1 activation is not focused on any one point, but distributed throughout the M1 area. Similarly, because outputs from the M1 hand area converge from large territories to specific finger muscles, the territories outputting to two finger muscles often overlap (Schieber, 1999). Instead of specific somatotopic areas controlling certain fingers, Schieber (1999) hypothesized that somatotopic gradients in the M1 hand area controlled finger movement. He studied stroke patients with resulting hand weakness, and the effects of the lesions on the M1 area. What he found was uniform weakness in all fingers, with no single finger exhibiting greatest weakness, suggesting that control of specific fingers is seen throughout the M1 hand area, and not at any localized point.

Previous studies explored the interaction between the central and peripheral factors and its affect on finger interdependency. Zatsiorsky, Li and Latash (1998) observed enslaving effects (EE) during multi-finger force production. Subjects pressed their fingertips on uni-directional force sensors at maximal voluntary contraction (MVC). Fifteen different combinations of all four fingers were randomly tested, as a one, two, three, or four-finger task. If the non-task fingers wanted to unconsciously produce forces, the subjects were encouraged to let them do so. Enslaving effects of a specific non-task finger were compared to the finger's MVC as a task finger.

Several results were found after observing the EE during MVC tasks. Non-task fingers produced large amounts of force, approximately 54.7% of the maximal force produced during their single finger task condition. In addition, the results showed that enslaving influences from one adjacent finger to another were symmetrical, influencing each

other similarly. The study also found that tasks involving more than one finger had lower enslaving from the non-task finger than single task conditions. For the IM (index and middle) task condition, the ring finger only activated 24.4% of its maximal force, whereas in the M task, it produced 43.0%. This effect was called occlusion. Finally, EE were larger for fingers closest to the task finger. As the distance between the task finger and the non-task finger grew, the EE decreased. The phenomenon was called the proximity hypothesis.

From these results Zatsiorsky, Li and Latash (1998) formulated a neural network model that consisted of an input that begins to formulate a drive, or request; a second layer transforming the drive into an input, and a third layer corresponding to finger force output. From the modeling results, they hypothesized that a direct command resulting in direct output of finger force did not exist. Instead, finger forces are produced when the command sent to the task finger is weighted relatively to the commands sent to the other fingers.

Zatsiorsky, Li and Latash (2000) continued to investigate EE in isometric force production in the fingers by having subjects perform MVC as a one, two, three or four-finger task. A new experimental technique examined the MVC at different points of force application: the middle of the distal phalanx (DP), at the distal interphalangeal (DIP) joints, and at the proximal interphalangeal (PIP) joints. This allowed for different loading conditions for the flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), and intrinsic muscles of the hand. Zatsiorsky, Li and Latash (2000) hypothesized that intrinsic hand muscles would not produce EE; the different loading conditions would activate different muscles and would clarify the role of peripheral and central factors in these different conditions.

Enslaving effects did occur at the non-task fingers. A parallel increase in the non-task enslaving force was noticeable as force production increased in the task finger. Enslaving also decreased as the distance between task and non-task fingers increased, supporting the results found in their previous study (Zatsiorsky, Li and Latash, 1998). However, contrary to their hypothesis, EE were similar in all three locations where the MVC was tested (middle of the DP, DIP joint, PIP joint). Though the contribution of the extrinsic (FDP and FDS) and intrinsic muscles changed with each position, the overall enslaving effect remained the same in all three conditions. Thus EE were found to be present in muscles that were anatomically separate, with broad neural interactions controlling flexor muscles contributing to finger enslaving. Zatsiorsky, Li and Latash (2000) also concluded that since coordinated force patterns are most prevalent at our fingertips, EE that do occur are a result of not only peripheral tendon connections and extrinsic muscles, but also from intrinsic hand muscles, which are as involved during fingertip force production tasks as extrinsic muscles.

While Zatsiorsky, Li and Latash (2000) investigated force (kinetic) enslaving by evaluating force inputs and outputs, Hager-Ross and Schieber (2000) investigated motion (kinematic) enslaving, where the involuntary angular movement of non-task fingers was observed. They evaluated the ability of human subjects to move each finger independently one at a time, comparing finger independence of subjects' right and left hands, observing independence changes at varying frequencies (2 Hz to 3 Hz), and evaluating interjoint coordination across the DIP, PIP, and MCP joints. In order to do so, two indexes were calculated from the relative motion slopes of the task and non-task fingers. The individuation index (II) was used as a measure of how independent the task finger moved.

The II for the task finger equaled 1 minus the average relative motion slopes of the non-task fingers:

$$II_j = 1 - \frac{(\sum_{i=1}^n |S_{ij}|) - 1}{n - 1},$$

where II_j was the individuation index for the j th task finger, S_{ij} was the slope of the relative motion of the i th finger during the j th instructed movement, and n was the number of fingers. An individuation index close to 1 indicated no movement of the non-task fingers, with II 's closer to 0 indicated more non-task finger movement with the task finger. A similar index, a stationarity index (SI), quantified a finger's movement as a non-task finger. The SI equaled 1 minus the average relative motion slope of a non-task finger:

$$SI_i = 1 - \frac{(\sum_{j=1}^m |S_{ij}|) - 1}{m - 1},$$

where SI_i was the index for the i th finger during m task movements. A finger close to 1 remained stationary as a non-task finger.

Motion enslaving was found to occur when the task finger voluntarily moved. The middle and ring fingers had the lowest II, as well as the lowest SI. Subsequently, the fingers having the highest II (like the thumb and index finger) also had the highest SI, suggesting that the factors enabling the independence of a finger reduced its enslaving properties. Finger independence did not appear to differ between the dominant and nondominant hands. Furthermore, finger independence was found to be less during higher frequency (3 Hz) movements than at a lower self-paced frequency (2 Hz). When evaluating interjoint coordination, angular motion was greatest at the PIP joint than at the MCP and DIP joints. In regards to motion enslaving, Hager-Ross and Schieber (2000) noted that their findings were

similar to previous studies testing force enslaving. They did hypothesize, however, that the increased enslaving found during the higher frequency conditions may have been due to a combination of higher viscoelastic coupling between the fingers as well as greater functional activation in the M1 (Rao, et al., 1996).

Whereas Hager-Ross and Schieber (2000) studied finger independence with compound voluntary movements (the hand was not restricted at any joint), Li et al. (2004) investigated motion enslaving in voluntary movements across the DIP joint of the task finger. Since the DIP joint is flexed by a single tendon of the FDP, the independence due to subsequent separate muscular compartments of the FDP could be indirectly quantified. Li et al. (2004) focused on the enslaving effects caused by the FDP in their experiment comparing the relative enslaving indices of each non-task finger across the same joint and multitendoned muscle.

Subjects had the PIP and MCP joints fixed and arm and wrist secure as they were instructed to flex the DIP joint of the task finger as fast as possible. Separators were placed in between the fingers in order to ensure adjacent fingers did not touch. Angular displacements, velocities, and accelerations of each individual finger were measured and used to calculate independence indices (Π) for the task finger:

$$\nu_j = \frac{X_j}{\sum_k X_k},$$

as a ratio of the maximal angular displacement (X_j) of the task finger to the sum of the maximal displacements (or velocities or accelerations) of the non-task fingers (X_k). Complete task finger independence resulted in an index of 1. Time delay between the task and non-task

fingers was also examined via a cross-correlation function of the acceleration curves of the task and non-task fingers.

Time-series curves of the non-task fingers' response to task finger movement revealed highly correlated movement from the non-task fingers, indicating motion enslaving. Enslaving effects were noticeable in angular displacement, velocity, and acceleration measures. Each task finger imposed significant enslaving effects on adjacent non-task fingers as well.

The index finger's enslaving effects were significant on the middle finger, and negligible on the ring and little fingers. The index finger also had the highest independence index, corroborating with evidence that the FDP compartment in the index finger was more independent as a muscle head (Fahrer, 1981). Li et al. (2004) also noted that the independence index scores from their study were "analogous" to the Hager-Ross and Schieber's individuation index scores, particularly to those of the index and little fingers. However, the independence index was lower when converted to the individuation index measures used by Hager-Ross and Schieber (2000), suggesting lower independence (thus more enslaving) at the DIP joints compared to the compound joint movements of a finger.

Based on the results of the motion tasks, Li et al. (2004) found that the angular displacements, velocities and accelerations of the task fingers were similar across the DIP joints, and that motion enslaving effects were limited to non-task fingers directly adjacent to the task finger, unlike previous force enslaving studies that found enslaving spread to non-adjacent fingers as well (Zatsiorsky, Li and Latash, 1998; Zatsiorsky, Li and Latash, 2000). However, those values directly adjacent to the task finger were also significantly higher than force enslaving values found in previous studies (Zatsiorsky, Li and Latash., 2000). Li, et al.

(2004) hypothesized that the differences could be attributed to the task differences that the various studies employed. Ultimately, Li et al. (2004) concluded that the interactions between the tendinous components of the FDP suggested an even more complex interaction of multiple muscles was needed to achieve high levels of dexterity in finger tasks.

While force and motion enslaving was explored, Lang and Schieber (2004) studied the effects of finger independence about the MCP joint in voluntary and involuntary movement. The task finger was secured to a paddle and was moved passively by a motor through a large arc flexion/extension range of motion (approximately 80 degrees) and a small arc range (40 degrees). In the voluntary condition, the procedure was repeated without the assistance of the motor. Joint angles were recorded from a goniometer and used to calculate an individuation index (II):

$$II = 1 - \frac{E_{noninstructed}}{E_{instructed}},$$

where $E_{noninstructed}$ was the average joint angle of all the joints (MCP, PIP, and DIP) of the non-task fingers, and $E_{instructed}$ the average joint angle of all the joints of the task finger. In order to separately evaluate voluntary and involuntary movement, indexes were derived to quantify mechanical coupling constraints (PCI) and neuromuscular control (ACI):

$$PCI = \frac{passiveE_{noninstructed}}{passiveE_{instructed}} \quad \text{and} \quad ACI = \left(\frac{activeE_{noninstructed}}{activeE_{instructed}} \right) - PCI,$$

where $passiveE_{noninstructed}$ was the average involuntary joint angle of all the joints (MCP, PIP, and DIP) of the non-task fingers, and $passiveE_{instructed}$ the average joint angle of all the joints of the task finger, and where $activeE_{noninstructed}$ was the average voluntary joint angle of all the joints (MCP, PIP, and DIP) of the non-task fingers, and $activeE_{instructed}$ the average joint angle of all the joints of the task finger, minus the PCI condition.

Lang and Schieber (2004) found that the II's during the voluntary condition were found to be lower than the II's during the involuntary condition, indicating less independence for the fingers in the voluntary condition. More specifically, II's for the middle, ring and little fingers in both large and small arc ranges were smaller in the voluntary condition. In terms of trying to quantify the limitations of independence, Lang and Schieber (2004) found that the PCI was greatest in the index, middle and ring fingers, indicating that the finger interdependence in these fingers was due to mechanical coupling between the fingers. Meanwhile, the ACI was greatest in the ring and little fingers during large-arc movements, but also more variable between subjects than the PCI's.

The results found by Lang and Schieber (2004) assumed a linear relationship between the voluntary and involuntary effects of movement, since the ACI subtracted the PCI from its calculations. Despite that, they reasoned that mechanical coupling between the fingers was the important factor in finger interdependence, more so than neuromuscular control factors.

Though previous studies had considered kinetic inputs and kinetic outputs, as well as kinematic inputs and kinematic outputs, Kim, et al. (2008) linked the two and studied finger interdependence in terms of kinematic inputs (motion of task finger) and kinetic outputs (force readings). The task finger followed a ramp template that flexed the finger about the MCP joint from 0° to 45° (flexion movement), then back to 0° (extension movement). While this occurred, force sensors attached to the non-task fingertips recorded involuntary force outputs. Each finger was the task finger, and seven different durations of the trials were tested (30, 25, 20, 15, 10, 7.5, and 5 seconds). The force enslaving values from the non-task fingers were calculated with an enslaving index:

$$E_{ij} = \frac{\Delta F_i}{\Delta \alpha_j},$$

where ΔF_i was the force change of non-task finger i , and $\Delta \alpha_j$ was the angular position change of the task finger j .

Kim, et al. (2008) found that the index finger had greatest independence among task fingers, supporting results found in previous studies (Hager-Ross and Schieber, 2000; Lang and Schieber, 2004; Li, et al., 2004). The study also found additional support for the proximity hypothesis, first mentioned in Zatsiorsky, Li and Latash (1998), as the middle finger had the greatest enslaved force for the index and ring fingers (as task), index for the middle finger task, and the ring for the little finger task. Enslaving was also found to be higher overall when the task finger was in the flexed position (0° to 45°), which was contrary to what they expected to find. Also, while previous studies alluded to mechanical coupling as the greater factor in finger interdependence (Lang and Schieber, 2004), Kim, et al. (2008) argued that neural factors played more of a dominant role in finger interdependence, since previous viscoelastic force reactions were not present in the study, pointing more towards neural signal levels influencing enslaving rather than a peripheral constraint. Although the changes in movement speed affected the kinematic readings of the task finger, there was no change in the enslaved force reading from the non-task fingers.

Not only did previous studies address the kinematic and kinetic variables associated with finger interdependency, or examine different movement conditions in order to quantify central and peripheral factors related to finger interdependency, but Shim et al. (2006) compared the finger interactions during maximum voluntary force (MVF) in children and adults, in order to investigate age-related changes to finger interdependency in both flexion

and extension directions. Twenty-five typically developing children between 6-10 years of age were tested and compared with twenty-five college students between 20-24 years of age. Subjects produced a maximum isometric force for each finger and as a four-finger task, in both flexion and extension directions. Force enslaving was calculated as an index:

$$FE = \frac{\sum_{j=1}^n \left[100\% \times \sum_{i=1}^n (F^{ij} / F_{\max}^i) / (n-1) \right]}{n},$$

where $n=4$, F_{\max}^i was the maximum force produced by finger i , and F^{ij} was the force produced by the non-task finger i during j finger maximum force task (with i not equal to j).

Shim et al. (2006) found an increase in the MVF values as the age of the children increased in both flexion and extension directions, with differences between the children and the adults larger in the flexion direction. The index and middle fingers also showed the largest MVF values as the task finger. Also, as age increased, the FE indices decreased in children in both flexion and extension directions, but remained the same for adults. Thus as the children increased in age, more independency was found in their fingers, due to the smaller FE values. Interestingly, flexion independency for children was very similar to adults, whereas extension independency lagged behind. Shim et al. (2006) speculated that everyday manipulation tasks provided a greater amount of learning experiences available for flexor muscles, allowing the fingers to gain more independence in the flexion direction earlier than the extension direction.

Oliveira et al. (2008) expanded on previous studies by Shim (Shim, et al., 2004; Shim, et al., 2007) and investigated age-related changes via MVF and finger interdependency on the elderly (classified as sixty and older), using the same experimental paradigm followed

in Shim, et al. (2007) as a model. Oliveira et al. (2008) looked to expand and develop a developmental picture of finger interdependency throughout the lifespan, as well as confirm the proximity hypothesis in the elderly population.

Oliveira et al. (2008) found that MVF values were much greater in flexion than extension, speculating that the difference was due to the differences in muscular strength between the flexor and extensor muscles. The maximum MVF values predictably decreased from the values of the young adults, though the males had greater MVF values than the females. When looking at FE values, enslaving was found to be greater in the extension direction than the flexion direction, again due to the frequent use of flexor muscles as opposed to the extensor muscles in everyday tasks. The FE difference between the flexion and extension direction was greater in the elderly group than in the young adults, further suggesting that finger independency increased throughout the lifespan. Finally, the proximity hypothesis was once again confirmed in the elderly population, not affected by age.

Chapter 3 – Research Design

Subjects

Fourteen right-handed male ($n = 7$) and female ($n = 7$) young adults (22.3 ± 3.1), participated as subjects in this study. All subjects were considered right-handed based on a greater than 90% score on the Edinburgh Handedness Inventory (Oldfield, 1971). Subjects filled out a questionnaire in order to confirm that they did not have a previous history of neurological or orthopedic disorders. Subjects engaged with any activities requiring specific finger skill, such as piano playing, or any type of strength training programs involving fingers were excluded. All subjects performed the tasks free from any influences of medication, and all subjects were asked to refrain from strenuous hand or forearm exercises 24 hours prior to the testing day. Informed consent was obtained from each subject prior to testing, according to the procedures approved by the University of Maryland Institutional Review Board (IRB).

The hand length of each subject was measured between the distal crease of the wrist and the middle finger tip, as the subject positioned the palm side of their right hand and lower arm on a table, with all finger joints extended. The hand width was measured between the radial side of the index finger MCP joint and the ulnar side of the little finger MCP joint. The length starting from the center of the MCP joint to the tip of each finger was also measured. Subject anthropometry is shown below in Table 3.1. The subject was also asked to flex and extend each finger voluntarily at the MCP joint (with the PIP and DIP joints in an extended, straight configuration) to the finger's maximal ability. The angular position was measured by the goniometer, and the prescribed voluntary and involuntary movement tasks for the experiment were set at 80% of the measured range of motion.

Table 3.1- Subject age, hand widths, hand lengths, finger lengths. Mean \pm SD

	Age (yrs)	Hand Length (cm)	Hand Width (cm)	Index (cm)	Middle (cm)	Ring (cm)	Little (cm)
Subjects (n=14)	22.3 \pm 3.1	8.1 \pm 0.8	18.7 \pm 1.5	9.0 \pm 0.7	10.5 \pm 0.8	9.6 \pm 0.7	7.4 \pm 0.6

Apparatus

An aluminum L-shaped lever with a track panel was vertically positioned to avoid the effects of gravity on the task finger during angular involuntary and voluntary movements. The lever was attached snugly into a fitted slot on a rotating moment arm. Four one-dimensional force/moment sensors (Piezotronics PCB, SN 22787; grey dots in Figure 2.1) were individually attached on threaded aluminum rods, each attached to the fingers. The horizontal positions of the sensors on the panel were adjustable along the axis parallel to the forearm (X-axis) to accommodate subjects' hand and finger anthropometry. Subjects inserted each finger into an aluminum thimble attached to each sensor. Plastic tile pieces were attached to the surface of the sensors in order to prevent heat transfer from the fingers to the sensors, while maintaining a snug fit over each of the finger pads. Splints were wrapped around the length of the finger from the PIP to the DIP joint to restrict their movement. A thumb splint (Futuro, Beirsdorf, Inc.; not shown in Figure 3.1) was worn over the thumb to prevent additional extraneous movement that may have interfered with the L-shaped lever. For involuntary movement tasks, the subject had the task finger attached to the L-shaped lever via the threaded rod, while the non-task fingers were securely fastened to the vertical aluminum track directly opposite of the L-shaped lever (Figure 3.1). The position of the fingers and the respective threaded rods were adjusted by a track from an aluminum panel,

which enabled different fingers to become the task finger quickly and comfortably. Signals from the sensors were conditioned, amplified, and digitized at 1000 Hz using a 16-bit A/D board (PCI 6034E, National Instruments Corp.) and custom software made in LabVIEW (LabVIEW 7.1, National Instruments Corp.). A desktop PC computer with a 19" monitor (Dimension 4700, Dell Inc.) was used for data acquisition. On-line feedback of the task finger angular position was displayed on the monitor screen during both involuntary and voluntary movement conditions. During both involuntary and voluntary movement tasks, the angular position of the task digit was monitored with a goniometer (Biometrics Ltd, F35) attached to the MCP joint via the anterior position of the hand.

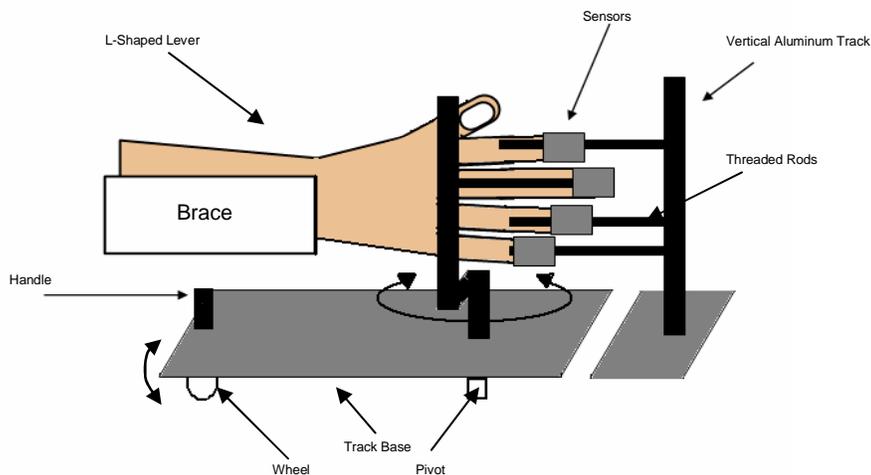


Figure 3.1 – Experimental apparatus and subject position during experiment. The brace and splint are used to minimize movement in arm and fingers. The grey rectangles on the fingertips represent the sensors. The moment arm with the L-shaped attachment, which moves the task finger during passive trials, is represented by the panel.

Procedure

The finger pads of the subject were secured within the aluminum thimble with athletic tape wrapped around the thimble, preventing lateral movement that could have

caused separation from the force sensor. Plastic tiles were also removed or added to the thimble to ensure a snug yet comfortable fit for each finger. Wood splints were attached to each finger with athletic tape at a length approximate to the subject's distal and proximal joints to keep the MCP joint angles consistent at 180° (an extended configuration of fingers).

The subject faced the testing table, sitting on an adjustable chair with their feet on the floor. The upper arm of the subject was positioned at approximately 45° of abduction in the frontal plane and 45° of flexion in the sagittal plane, and the elbows positioned at approximately 90° of flexion. The forearm was secured on the wrist and forearm brace with multiple Velcro straps. The experimental setup described above was used to measure moment responses of non-task digits caused by the voluntary and involuntary angular movements of the specified task finger. There were four task finger conditions (index (I), middle (M), ring (R), and little (L) fingers of the right hand), with the order of conditions balanced across subjects. The thumb was omitted from the experiment due to the anatomical and functional differences between the thumb and the remaining fingers (MacKenzie and Iberall, 1994; Marzke and Marzke, 2000; Van De Graaff, 2000; Shim, 2005). Subjects were specifically asked to relax the hand and fingers while not voluntarily moving any of the non-task fingers, to prevent interference with the experiment. The experimenter positioned the non-task fingertips on the force sensors (secured to the aluminum track opposite of the L-shaped lever), while the angular position of the task finger at the relaxed position was measured and set as the 0° mark. The task finger's sensor was attached to the track on the L-shaped lever and in the thimble positioned at the prescribed 0° mark of angular position.

A three second pause marked the beginning of the data collection program, and during the involuntary movement condition, the experimenter moved the moment arm at its

handle (Figure 3.1) and rotated the task digit into 18 flexion and extension cycles at maximum and minimum finger angles set at 80% of the ROM. During those cycles, the experimenter followed a preprogrammed sine-wave angular position time profile displayed on a monitor in order to maintain constant speed, as well as to match the ROM for the task digit. Real-time visual feedback allowed the experimenter to follow the sine profile as closely as possible by tracing over it. The angular position was recorded by the goniometer secured to the MCP joint of the task digit via the anterior position of the hand. The speed of angular movement was set at 0.5 Hz and 0.25 Hz (cycles/second).

The threaded rod was removed from the task digit during the voluntary movement condition, while the non-task fingers were attached to the track opposite of the lever. Subjects were given time to practice the voluntary movement, in order to imitate the angular movement trajectory used during the involuntary movement condition. The same sine profile template used from the involuntary condition was also used in the voluntary movement condition; the subjects traced the trajectory shown with the movement of the task finger. The goniometer was used to measure the angular position of the task finger during voluntary movement.

Data Processing

The raw force and moment data recorded from the sensors was digitally low-pass filtered with a 2nd order, zero-lag Butterworth filter at 6 Hz of cutoff frequency (Schieber and Santello, 2004). The analysis was taken from fifteen flexion-extension cycles from the middle of each trial.

The frequency-response functions (*FRF*) for each trial were computed from the angular displacement of a task digit to the force responses of non-task digits. The Fourier

transform of angular displacement of a task digit divided by the Fourier transform of force responses of each non-task digit obtained the *FRF*. *FRF* is a complex-valued function and the enslaving index for gain(g_{ij}) was calculated as the absolute value of the *FRF*:

Two factors allowed the FRF to be advantageous to use. Since the FRF gave us the gain value, there was no need to calculate the gain index via slope and area calculations. Also, due to the number of cycles that the task finger performed (fifteen flexion/extension trials of eighteen flexion/extension cycles), there was a certain variability among the gain values. Calculating multiple slope and area values would be difficult and time-consuming. The FRF simply outputted one value, taking into account all the cycles.

The enslaving index, or the average of non-task finger gains by one task finger movement, was calculated using the equation below:

$$g_{enslaving}^j = \sum_{i=1}^n g^{ij} / n - 1; \quad i \neq j, \quad n = 4$$

In order to test the proximity hypothesis (i.e., greater finger enslaving of non-task fingers whose proximity is greater to task fingers during task finger trials) (Zatsiorsky Li and Latash, 1998; Zatsiorsky, Li and Lastash, 2000), the average value of non-task finger forces across the fingers adjacent to (F_{adj1}), second adjacent to (F_{adj2}), and third adjacent to (F_{adj3}) the task fingers was taken:

$$F_{adj_k} = \sum_{j=1}^m F^{adj_j} / m,$$

where $k=1$, $k=2$, and $k=3$, j represents the non-task fingers adjacent to, second adjacent to, and third adjacent to the task finger, and m represents the number of non-task fingers.

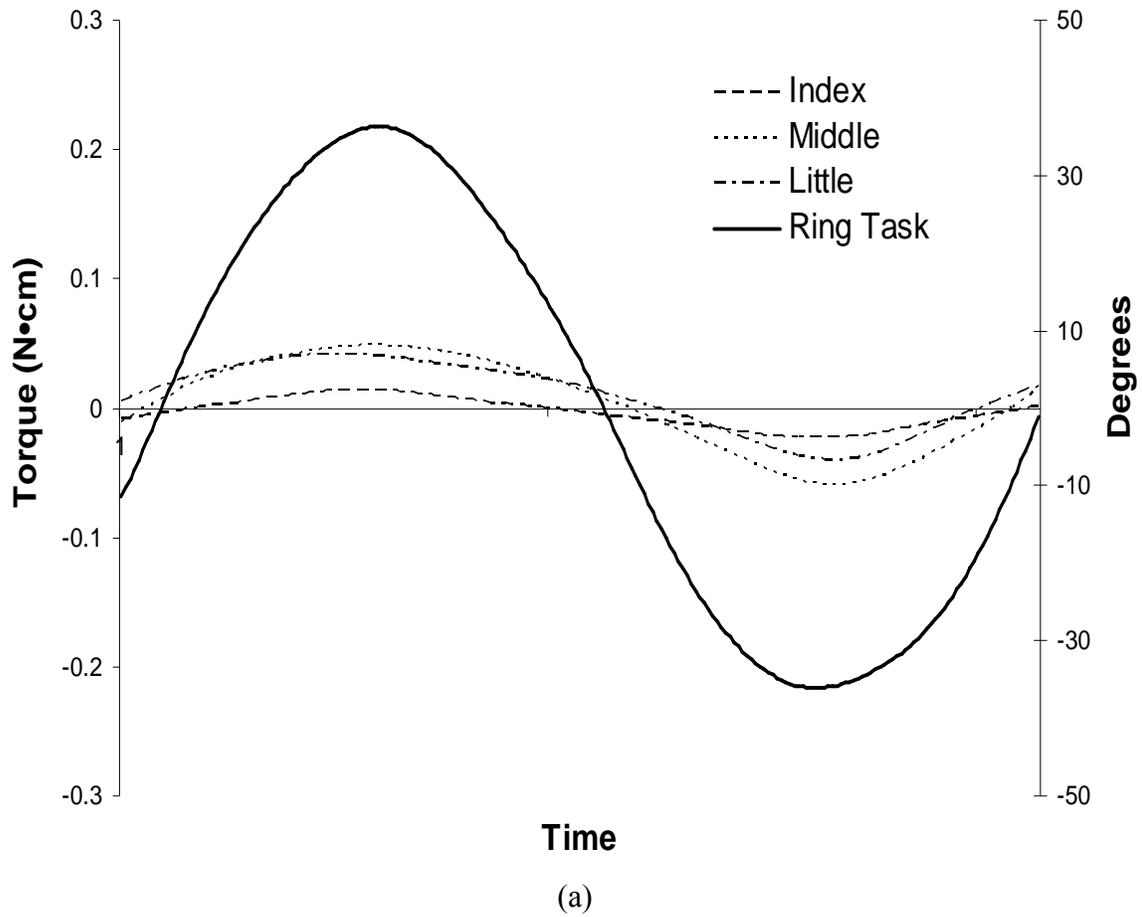
Statistical Analysis

Standard descriptive statistics and a three-way repeated measures ANOVA was performed with a 2(*MOVEMENT*: Voluntary, Involuntary) x 2(*SPEED*: 0.5 Hz, 0.25Hz) x 4(*FINGER*: Index, Middle, Ring, Little) matrix to analyze force enslaving values. Three-way repeated measures ANOVA with a 2(*MOVEMENT*: Voluntary, Involuntary) x 2(*SPEED*: 0.5 Hz, 0.25Hz) x 3(*PROXIMITY*: F_{adj1} , F_{adj2} , F_{adj3}) matrix was used to test for the proximity hypothesis. The Bonferroni corrections were used for significance adjustments for multiple comparisons. The level of significance was set at $p=.05$.

Chapter 4 – Results

Results

All subjects performed the task in both involuntary and voluntary movement conditions within different speeds (0.5 and 0.25Hz). Figure 4.1 illustrates the torque profiles produced by a typical subject's ring finger trial in the involuntary (a) and voluntary (b) movement conditions at 0.5 Hz.



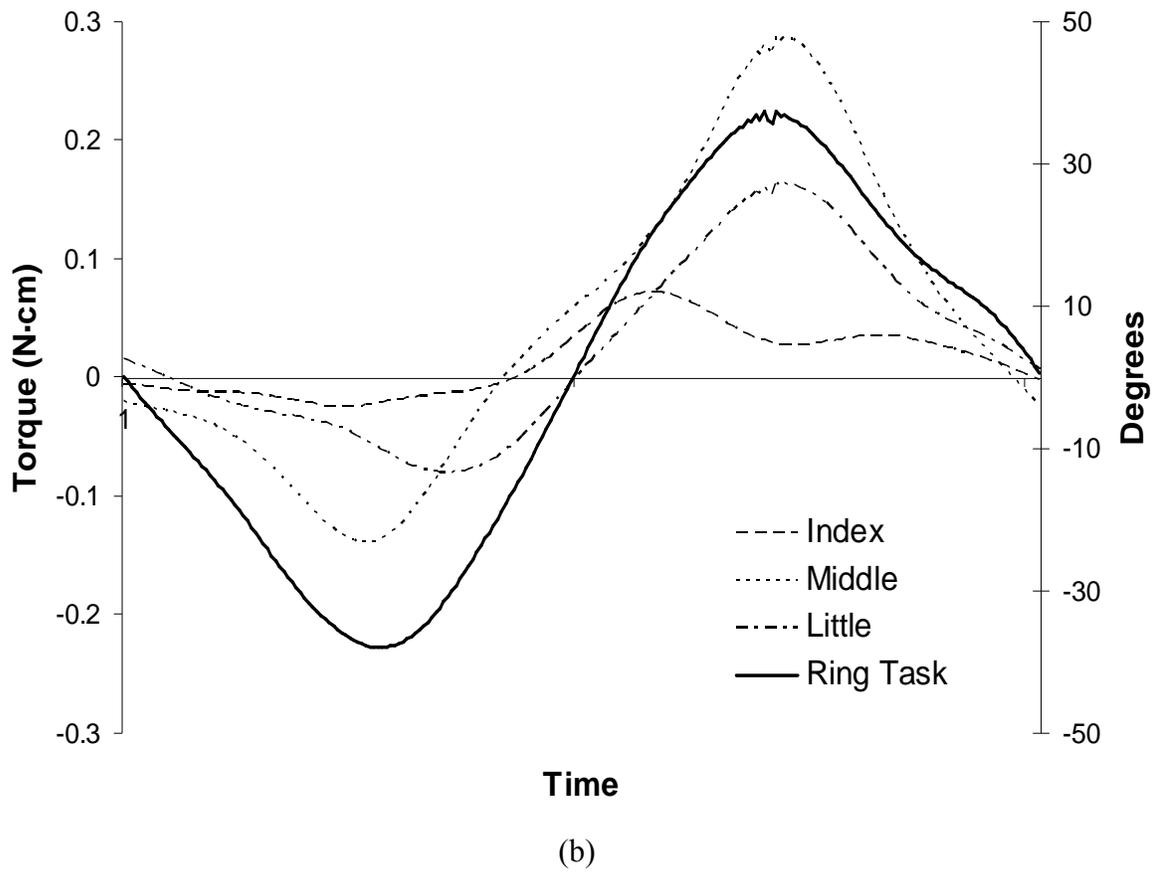


Figure 4.1 – Representative data profile for a typical subject’s trial in the involuntary (a) and voluntary (b) condition at 0.5 Hz. Task finger (in bold) units are in degrees, non-task fingers are in units of torque (N·cm).

Table 4.1 – Average enslaving indices ($M \pm SD$) across all subjects.

Voluntary		<i>NT Finger</i>				<i>Average Enslaving Values (N·cm/Deg) M ± SD</i>			
	Task Finger	<i>Index</i>	<i>Middle</i>	<i>Ring</i>	<i>Little</i>				
0.5 Hz	Index	-	0.0331 ± 0.019	0.0099 ± 0.008	0.0029 ± 0.003				
	Middle	0.0437 ± 0.034	-	0.0848 ± 0.042	0.0123 ± 0.015				
	Ring	0.0109 ± 0.009	0.0819 ± 0.054	-	0.0047 ± 0.034				
	Little	0.0057 ± 0.004	0.0112 ± 0.009	0.0455 ± 0.020	-				
0.25 Hz	Index	-	0.0399 ± 0.025	0.0130 ± 0.014	0.0048 ± 0.003				
	Middle	0.0556 ± 0.041	-	0.0960 ± 0.068	0.0173 ± 0.015				
	Ring	0.0133 ± 0.008	0.1064 ± 0.074	-	0.0431 ± 0.023				
	Little	0.0062 ± 0.004	0.0119 ± 0.008	0.0541 ± 0.024	-				
Involuntary		<i>NT Finger</i>				<i>Average Enslaving Values (N·cm/Deg) M ± SD</i>			
	Task Finger	<i>Index</i>	<i>Middle</i>	<i>Ring</i>	<i>Little</i>				
0.5 Hz	Index	-	0.0518 ± 0.029	0.0145 ± 0.011	0.0072 ± 0.007				
	Middle	0.0404 ± 0.022	-	0.0404 ± 0.022	0.0070 ± 0.006				
	Ring	0.0123 ± 0.013	0.0563 ± 0.047	-	0.0238 ± 0.016				
	Little	0.0061 ± 0.005	0.0146 ± 0.012	0.0323 ± 0.021	-				
0.25 Hz	Index	-	0.0548 ± 0.029	0.0126 ± 0.006	0.0064 ± 0.005				
	Middle	0.0569 ± 0.036	-	0.0492 ± 0.026	0.0065 ± 0.004				
	Ring	0.0169 ± 0.017	0.0662 ± 0.044	-	0.0269 ± 0.018				
	Little	0.0079 ± 0.008	0.0198 ± 0.020	0.0402 ± 0.037	-				

Finger Interdependency

Finger interdependence was quantified as the average ratio of finger torque at the MCP joint to the angle of task finger movement across fifteen flexion and extension cycles of the task finger (N·cm/Deg). Average enslaving indices across non-task fingers and speed are shown in Table 4.1. When enslaving indices were calculated across movement conditions, the voluntary condition had greater average enslaving values than the involuntary condition (Figure 4.2). In addition, the middle and ring fingers demonstrated higher enslaving indices when compared to the index and little fingers in both conditions (Figure 4.2). Average enslaving indices for all non-task fingers were also found to be greater at 0.25 Hz than at 0.5 Hz (Figure 4.3). These findings were supported by a three-way repeated measures ANOVA that showed significant main effects of SPEED [$F(1,13) = 28.475, p < 0.001$], MOVEMENT [$F(1,13) = 8.946, p = 0.01$], and FINGER [$F(3,11) = 4.705, p = 0.024$]. An interaction effect

was found between the MOVEMENT x FINGER [$F(3,11) = 6.008, p = 0.011$] factors; no interaction effects were found between SPEED and the two factors.

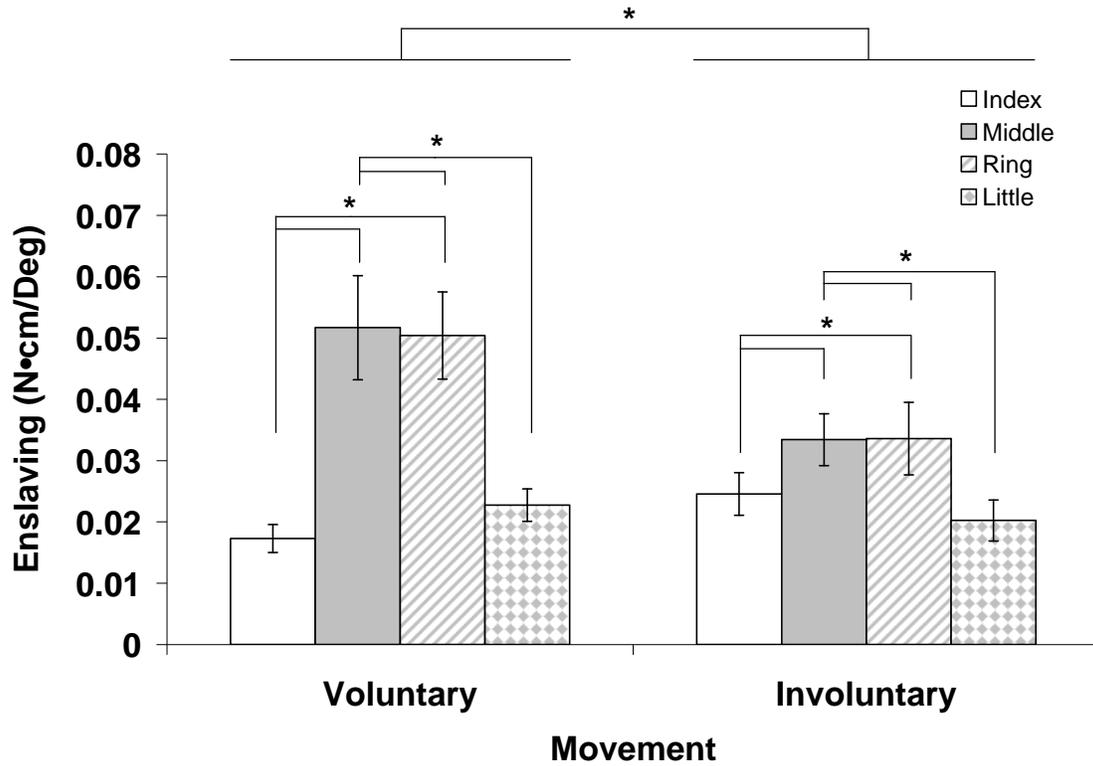


Figure 4.2 – Enslaving indices during voluntary and involuntary movement conditions. Average and standard error (SE) values across all subjects are shown.

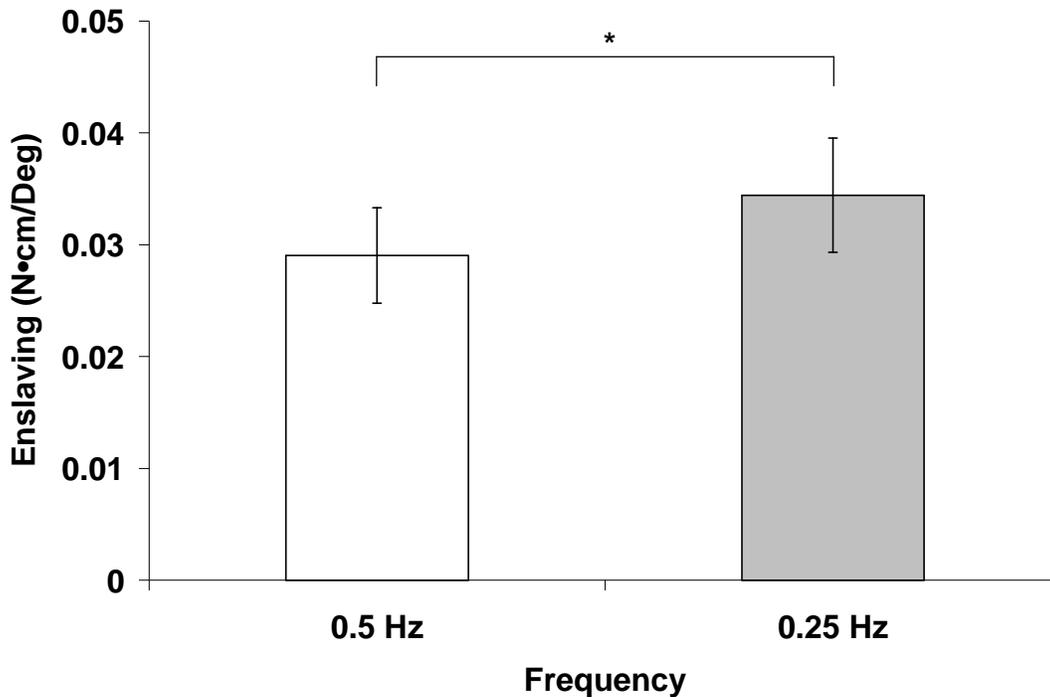


Figure 4.3 – Force enslaving indices during 0.5 Hz and 0.25 Hz conditions. Average and standard error (SE) values across all subjects are shown.

Finger Proximity

The average values of non-task finger forces were calculated across the fingers adjacent to (F_{adj1}), second to, (F_{adj2}), and third to (F_{adj3}) the task fingers in order to calculate the proximity hypothesis. F_{adj1} values were greater than the F_{adj2} and F_{adj3} values, suggesting that the non-task fingers closer to the task fingers had greater enslaving indices than the non-task fingers farther from the task finger (Figure 4.4). Pair-wise comparisons for finger position also showed significant differences between the F_{adj1} and F_{adj2} ($p < 0.01$), F_{adj1} and F_{adj3} ($p < 0.01$), and F_{adj2} and F_{adj3} ($p < 0.01$) values. When comparing the F_{adj1} , F_{adj2} and F_{adj3} values between the involuntary and voluntary movement conditions, the F_{adj1} values were greater in the voluntary than the involuntary condition (Figure 4.4). However, the F_{adj2} and

F_{adj3} values were greater in the involuntary condition than the voluntary condition. All F_{adj} values were greater during the slower speed (0.25 Hz) than the faster speed (0.5 Hz) (Figure 4.5). In addition, the F_{adj1} values in both speeds were significantly larger than the F_{adj2} and F_{adj3} values. These results were supported by three-way repeated measures ANOVA that showed significant effects of FINGERPROXIMITY [$F(2,12) = 53.111, p=0.0001$] and SPEED [$F(1,13) = 35.085, p=0.0001$]. Interaction effects were found between the factors FINGER PROXIMITY x MOVEMENT [$F(2,12) = 8.654 p=0.005$], and FINGERPROXIMITY x SPEED [$F(1,13) = 0.602 p=0.006$], which was due to the large difference between the F_{adj1} values and the F_{adj2} and F_{adj3} values.

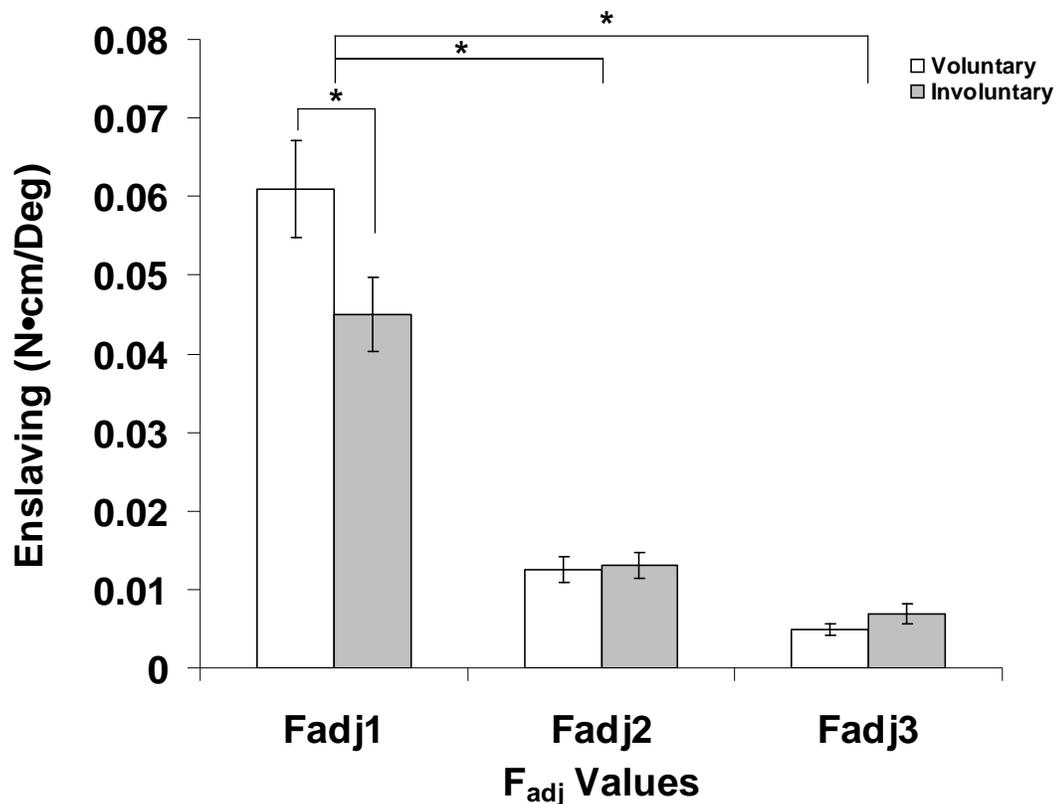


Figure 4.4 – Non-task (NT) finger enslaving values grouped by position to task finger (F_{adj1} , F_{adj2} , F_{adj3}) in both voluntary and involuntary movement conditions. Average and standard error (SE) values across all subjects are shown.

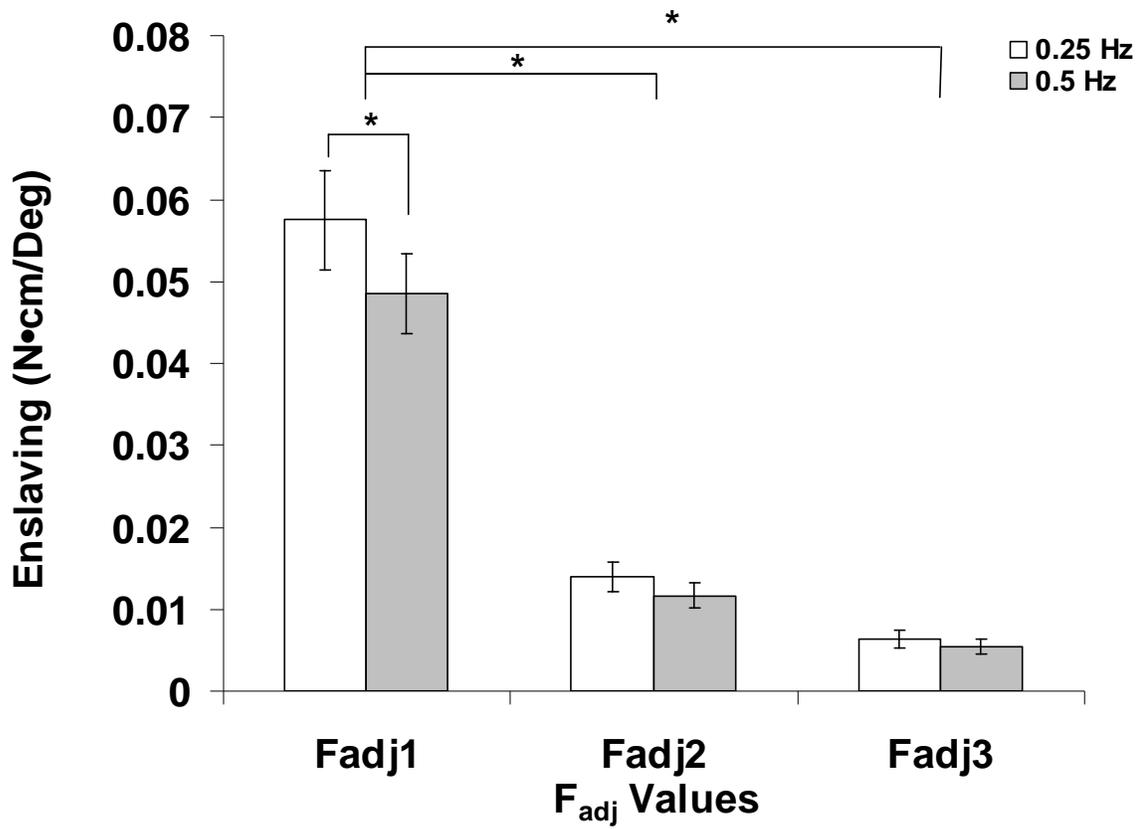


Figure 4.5 – Non-task (NT) finger enslaving values grouped by position to task finger at 0.5 Hz and 0.25 Hz. Average and standard error (SE) values across all subjects are shown.

Chapter 5 - Discussion

Finger interdependency was investigated during voluntary and involuntary movement conditions, as well as at different speeds, in order to quantify enslaving indices in different conditions and test the validity of the proximity hypothesis. The results showed that overall average enslaving indices were greater in the voluntary condition than the involuntary condition (0.036 N·cm/Deg vs. 0.028 N·cm/Deg, respectively), with a difference of 0.08 N·cm/Deg. Furthermore, enslaving indices were found to be greater during slower speeds, and calculated F_{adj} values supported the proximity hypothesis.

Central and Peripheral Factors of Finger Interdependence

Based on the results of this experiment, it was confirmed that voluntary movement of the task finger produced larger enslaving indices in the non-task fingers, which can be attributed to the role of both central and peripheral factors in finger control. Peripheral factors such as the architecture of the hand and forearm can mechanically couple fingers, resulting in finger interdependency. Skin and other soft tissues of the web spaces (Hager-Ross and Schieber, 2000; Schieber and Santello, 2004), as well as the structure of the extrinsic and intrinsic muscles of the hand and forearm, can also contribute to finger interdependency. The extrinsic hand muscles FDP and FDS are connected to multiple tendons within the fingers, which can result in non-task finger movement during involuntary task finger flexion (Leijinse, 1997). Other peripheral factors attributed to finger interdependency include interconnected tendons of certain muscles and other interconnections, such as the tendinous band between flexor pollicis longus and the FDP portion in the index finger (Hager-Ross and Schieber, 2000). Further examples include the

stretch reflexes activated during high frequency and large-arc movements from the spinal column that lack central nervous intervention.

Central factors, such as poor CNS control, also affect finger interdependence. Recent studies have shown movements to occur from stimulation across the whole M1 hand area. The area providing input to one particular muscle overlaps with the area of another muscle. Thus when movements of digits occur, more than one area may become activated. Lesion studies on macaque monkeys and humans have also supported the concept of a somatotopic gradient. Schieber (1999) studied the extent to which lesions involved in the M1 hand area were able to produce impairment on a single finger. Schieber (1999) found that overlapping somatotopic gradients in the M1 hand area controlled finger movement, as opposed to separate cortical areas specific to individual finger control. Divergence of a single M1 neuronal input to two different interneuron pools and consequently different muscles can also result in synchronous finger movement (Schieber and Santello, 2004; Oliveira, et al., 2008).

Zatsiorsky, Li, and Latash (2000) explored kinetic (force) enslaving and found that the force enslaving outputs obtained from maximal voluntary contractions (MVC) of various task fingers were similar at different points of force application. Though the muscle activity in the FDP, FDS, and INT muscles were different at different loading points (the middle of the distal phalanx, DIP joint, and PIP joint), the overall force enslaving remained similar in all conditions. The experimental results suggested that different peripheral factors, such as the inter-tendinous connections at the hand or the multi-tendinous extrinsic muscles, were not solely responsible for the force enslaving output that resulted. Central factors controlling the muscles were hypothesized to be a primary factor in the production of force enslaving (Zatsiorsky, Li, Latash, 2000) during voluntary force trials. The current results supported the

findings made by Zatsiorsky, Li, and Latash by investigating force enslaving in both voluntary and involuntary movement conditions.

Whereas the previous study explored force enslaving in the voluntary movement condition, the kinematic input and kinetic output model of the current experiment allowed for an analysis of enslaving indices from both involuntary and voluntary movement conditions, to evaluate any quantitative differences that may have occurred as a result. A difference of 0.08 N-cm/Deg was found between the voluntary and involuntary enslaving indices, which was attributed to the absence of central factors in the involuntary condition and the combined effect of both central and peripheral factors in the voluntary condition.

Studies by Li, et al., (2004) and Hager-Ross and Schieber (2000) obtained kinematic input and quantified values of kinematic output in order to investigate motion enslaving and finger independence across various finger joints. The specific enslaving effects of extrinsic muscles (namely, the FDP) on fingers were examined by restricting finger movement to only the DIP joint (Li, et al., 2004). Results showed that the index and little fingers had higher individuation indices (II) than the middle and ring fingers (0.812 ± 0.070 and 0.606 ± 0.148 to 0.530 ± 0.051 and 0.479 ± 0.099 , respectively) at the DIP joint. Along with the previous force study done by Zatsiorsky et al. (2000), the FDP muscle was mentioned as having a role in the independence of fingers, notably the index finger (Fahrer, 1981). Hager-Ross and Schieber (2000) also had findings analogous to the results found by Li, et al. (2004). Compound movements of the task and non-task fingers revealed high II's and stationarity indices (SI) for the index and little fingers.

Results from the current study corroborated with the previous examinations of motion enslaving. The enslaving indices as a value of gain, calculated through the use of the

FRF, were found to be greater in the middle and ring fingers and less in the index and little fingers, signifying greater stationarity (Hager-Ross and Schieber, 2000), and thus, greater independence. The findings were consistent in both involuntary and voluntary movement conditions; however, the enslaving values during the voluntary condition (0.052 N·cm/Deg and 0.050 N·cm/Deg, respectively) were significantly greater for the middle and ring fingers than the enslaving values found in the involuntary condition (0.033 N·cm/Deg and 0.034 N·cm/Deg, respectively), suggesting an additive effect of central and peripheral factors to force enslaving in the voluntary movement condition. The previous studies focused only on the voluntary movement condition and therefore did not have the opportunity to compare values between the involuntary and voluntary movement conditions.

Lang and Schieber (2004) explored both voluntary and involuntary movement conditions using kinematic inputs and outputs. Joint angles recorded by a glove were used to calculate three measures based on the range of motion (ROM) for the task finger and the ROM of the non-task finger: individuation indices (II), active contribution indices (ACI) and passive condition indices (PCI's). By having three separate measures from each movement condition, Lang and Schieber (2004) quantified peripheral factors mechanical coupling during the involuntary condition and central factors (neuromuscular control) during the voluntary condition and found that the PCI's were greatest in the index, middle and ring fingers, while the ACI's were greatest in the ring and little fingers, and during large-arc movements.

The current results were similar to the extent that for both voluntary and involuntary conditions, the middle and ring fingers had greater enslaving indices than the index and little fingers. Interestingly, the current study found that the little finger had low enslaving indices

during both the voluntary and involuntary movement condition, suggesting that it may have been similar in independence to the index finger. The current study did not use a glove to measure joint angles for non-task fingers, eliminating the need to account for an additional source of passive coupling. Instead, the subjects' non-task fingertips rested comfortably in their natural position in 1-dimensional sensors measuring kinetic output. The starting position of the fingers during both involuntary and voluntary movement conditions was consistent, all in completely relaxed positions, regardless of movement condition. The subjects were instructed to let the non-task fingers move if they felt like moving, and not to restrict such movement. Each finger was naturally separated and apart as well. Subjects in Lang and Schieber's experiment had metal rods placed in between the fingers, to prevent them from touching. This may have impeded the involuntary motion of the non-task fingers, especially considering that kinematic outputs were recorded. Subjects also "may have used co-contraction...to hold the other fingers in position" during the voluntary condition (Lang and Schieber, 2004). This may have unintentionally lowered the ACI values that were calculated during their experiment, though it may not have made much of a difference to the end results since each measure was viewed separately. The current study considered both central and peripheral factors as cumulative in affecting the voluntary condition, and recognize that passive factors have the possibility of changing while in the voluntary condition. Thus, though there was a 0.08 N·cm/Deg increase in enslaving from the involuntary to the voluntary condition, we cannot state that this was a linear change, or that it was due to a certain amount of specific factors. During the voluntary condition, a number of factors, both peripheral and central, may have contributed to the increase in enslaving in a non-linear, cumulative manner.

While the studies mentioned above had previously examined enslaving using kinematic inputs and outputs or kinetic inputs and outputs, Kim, et al. (2008) utilized the same strategy that was employed in our study and recorded the kinematic movements of the task finger while recording kinetic outputs of the non-task fingers. Kim, et al. (2008) recorded average enslaving while the task finger followed a trajectory template (0° - 45° as flexion segment, 45° - 0° as extension segment) shown on a computer screen. Both flexion and extension values were recorded at specific points in time. Enslaving was found to have been at its largest when moving through intervals with more flexion angle. The smallest enslaving index was found while the index finger was the task finger.

Though the study by Kim, et al. (2008) employed experimental parameters similar to the current study, there were some unique differences as well. Kim, et al. (2008) did not investigate the involuntary movement condition, choosing to focus on voluntary enslaving values. Also, though both of the studies recorded the task finger enslaving values in the flexion and extension direction (unlike several other studies previously mentioned (Zatsiorsky, Li and Latash 1998; Zatsiorsky, Li and Latash 2000; Li et al. 2004)), the definitions of “extension” were different. Kim, et al. (2008) defined extension as the segment of motion where the task finger moved from the 45° flexed position back to the 0° straight position. Therefore, though it was suggested that enslaving indices were not similar over the range of flexion and extension found in the task finger, had the definition of extension considered extension beyond the 0° position, different values may have been found. The current study had subjects follow a template that was set at 80% of the subject’s maximal ROM in both the flexion and extension direction. Both the flexion and extension force values

were incorporated in the calculation of the enslaving indices with the use of the FRF to obtain the enslaving indices discussed previously in the results section.

Effects of Speed on Finger Interdependence

Task finger movements in 0.25 Hz resulted in greater enslaving overall, as compared to movements in 0.5 Hz (0.034 N-cm/Deg and 0.029 N-cm/Deg, respectively). This finding was contrary to previous studies, where faster speeds resulted in higher enslaving indices and thus more finger interdependence. Increases in movement speed were related to increases in M1 activation in the hand area, potentially leading to an increase in central factors affecting enslaving at the non-task fingers (Rao et al., 1996). Hager-Ross and Schieber (2000) recorded kinematic outputs at two different speeds, one at a comfortable pace of ~2 Hz and the other at a faster pace of 3 Hz. The II's and SI's for each finger decreased at the faster speed. Due to the biomechanical constraints of the fingers, task fingers moving at higher velocities may pull non-task fingers at a higher velocity, which in turn could cause the nervous system to activate more muscle activity to counterbalance the viscoelastic forces (Hager-Ross and Schieber, 2000). Lang and Schieber (2004) controlled the speed at which their task fingers rotated, setting a velocity of 20°/sec, not wanting to elicit reflex responses. Other studies did not control for speed or frequency, but set different time constraints to finish a certain number of cycles (Li et al., 2004; Kim, et al., 2008). Not only was there no movement speed set as a precedent, the range of different speeds used was quite large and depended on the purpose of the study. The current study chose 0.25 Hz and 0.5 Hz so that the subjects could reasonably keep up with the pace without fatigue (Lang and Schieber, 2004; Li et al., 2004). We found at higher speeds, the task fingers had difficulty maintaining a consistent pace during both involuntary and voluntary movement conditions. A broader range

of movement speeds may need to be explored in order to better understand its role in the context of finger interdependency. Fatigue as a factor in finger interdependency may also be an important consideration that currently has not been explored in many studies that could play a role in finger enslaving.

Proximity Effects on Finger Interdependence

The proximity hypothesis (Zatsiorsky, Li and Latash, 1998) has been confirmed in many of the previous studies exploring finger manipulation (Zatsiorsky, Li and Latash, 2000; Li et al., 2004; Kim, et al., 2008; Oliveira et al., 2008). Oliveira et al. (2008) expanded the scope of the proximity hypothesis by testing enslaving values in the extension as well as flexion direction. In the calculations to determine the validity of the proximity hypothesis, the enslaving forces during the extension direction were not considered. The enslaving index for gain calculation considered the absolute value of gain, therefore the enslaving values were not discriminate by direction. Not only did Oliveira et al. (2008) calculate F_{adj} values in the extension direction, their study also used the average MVF values in order to calculate the F_{adj} values. In contrast, the current study used the average enslaving index of gain in order to calculate F_{adj} values. Also, Oliveira et al. (2008) confirmed the validity of the proximity hypothesis by computing MVF values from a voluntary condition of movement. The validity of the proximity hypothesis in both the voluntary and the involuntary movement condition was confirmed in the current study. The results showed a significant difference in the average F_{adj1} values between the voluntary and involuntary condition, as the F_{adj1} value was greater in the voluntary than the involuntary condition.

Previous studies had mentioned differences in the voluntary and involuntary movement condition (Lang and Schieber, 2004), but did not confirm or corroborate the

proximity hypothesis. This study may be the first to confirm the validity of the proximity hypothesis in both voluntary and involuntary movement conditions. In addition, we can speculate that the greater F_{adj1} value was caused by a combination of both peripheral and central factors found contributing to finger interdependence.

Li, et al. (2004) observed that motion enslaving was limited to adjacent fingers, while force enslaving spread to more distant fingers (Zatsiorsky, Li and Latash, 2000). Li et al. (2004) attributed that to a possible task difference that was found between the two studies, namely that with kinetic outputs, counterbalance forces were made from fingers farther away from the task finger in order to minimize pronation/supination moments about the longitudinal axis. While this may be true during voluntary movement, motor control strategies attempting to balance across the longitudinal axis are not present in involuntary movement. The F_{adj1} values in the current study were significantly larger than the F_{adj2} and F_{adj3} values in the involuntary and voluntary movement conditions. The current study utilized kinematic inputs to produce kinetic outputs. The similarity of the input task to the one used in Li et al (2004) may explain why the F_{adj1} values were greater. However, because the kinetic outputs were force outputs, the results also corroborate with Zatsiorsky, Li and Latash (2000), in that force enslaving spread to more distant fingers. Another possible factor could have been the experimental setup. Though kinetic outputs were utilized, the fingers and hands were situated in the vertical plane, negating the effects of gravity on the force outputs and perhaps minimizing the counterbalance forces made from the non-task fingers. This setup was similar to the one used by Li et al (2004), which may explain why the results were also similar to Li et al (2004). The setup used in the study by Zatsiorsky, Li and Latash (2000), in addition to the possible pronation/supination movements along the longitudinal

axis, may have had additional force outputs caused by the effect of gravity along the various joint positions as it rested on the sensor. The combination of gravity effects and counterbalance strategies may explain the additional forces found in the more distant non-task fingers, whereas in the current study, those factors were minimized by changing the experimental setup similar to Li et al (2004). Other refinements may be needed in order to investigate the possible effects of “outside” forces on outputs. Further studies may also be needed in order to elaborate and expand on the current understanding of the proximity hypothesis, especially in regard to its presence during involuntary movement conditions.

Chapter 6 – Conclusion

Limitations of current study

The current study calculated enslaving indices by taking the absolute value of all values. By doing so, we did not account for the role of extension and flexion in our results. A different method of calculating enslaving from oscillatory tasks could be employed in future studies in order to understand the role of flexion and extension forces into consideration. This study was limited to fully addressing the involuntary condition of movement by not monitoring all subjects with surface electromyograms (EMG) on flexor and extensor muscles to ensure the involuntary movements were not a product of stretch reflexes. Lang and Schieber (2004) monitored subjects with EMG by attaching surface electrodes over the radial portion of the extensor digitorum communis, the ulnar part of the FDP, and the volar portion of the flexor digitorum superficialis. It is noted that less than two percent of their trials were aborted due to unwanted muscular activity. In the experimental procedure, each subject was continually reminded to relax all the muscles in their hand and arm before each trial began. This verbal reminder seemed sufficient, as no one experienced any type of problem relaxing their hand and arm muscles. However, the use of an EMG machine would have eliminated the need for speculation.

Implications for current study

The results and findings provided by the study do open the doors to future areas of research. Studies on finger interdependency, specifically in the extension condition, have been limited (Shim, et al., 2006; Oliveira, et al., 2008). Expanding the scope of the current study to investigate the role of finger interdependency as it specifically relates to the flexion

and extension conditions in both voluntary and involuntary movement conditions would be beneficial. Currently, developmental studies have focused on finger interdependency in children, young adults, and elderly (Shim, et al., 2004; Shim, et al., 2006; Oliveira, et al., 2008) by investigating MVF tasks. Perhaps an investigation of enslaving from oscillatory tasks such as the one employed in the current study will shed new light on the role of task differences in finger interdependency. In addition, examining age-related changes of finger interdependency in both voluntary and involuntary movement conditions may provide additional insight on whether or not the role of central or peripheral changes as a person ages.

Finally, the knowledge of finger interdependency and the role of central and peripheral factors can provide a foundation for the improvement of hand and finger manipulation and dexterity. In fact, manipulation tasks require a synergistic approach of multiple digits, compensating for errors, in order to achieve the task goal (Shim, et al., 2006). Whether improving healthy subjects' coordination or coordination in children with developmental coordination disorder, much study has already been done in seeking to improve quality of life for people. The hope is that the findings from this study, though narrow in scope, will progress towards the goal of further improving digit control and manipulation in humans.

Conclusion

In summary the results showed that (1) finger interdependency increased when in the voluntary movement condition, (2) finger interdependency increased at slower speeds, and (3) the proximity hypothesis was confirmed for both the involuntary and voluntary movement condition. The current study provides insight in the role of peripheral and central factors in finger interdependency. Peripheral factors contribute to finger interdependency in

the involuntary movement condition, whereas combinations of peripheral and central factors contribute to finger interdependency during voluntary movement.

Appendix A

Subject ID:

EDINBURGH HANDEDNESS INVENTORY

Please indicate your preferences in the use of hands in the following activities *by putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put ++*. If in any case you are really indifferent *put + in both columns*.

		Left	Right
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (upper hand)		
9	Striking match (match)		
10	Opening box (lid)		
i.	Which foot do you prefer to kick with?		
ii.	Which eye do you use when using only one?		

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Appendix B

Subject ID:

Health Status Questionnaire

Name _____ Telephone _____

Address _____

Date of birth _____ Age _____ Height _____ Weight _____

Hearing impairment Yes ____ No ____ If yes, describe _____

Color blind Yes ____ No ____ Gender M ____ F ____

Years of education (high school = 12, college + 16) _____

Medications Are you presently taking or have taken any of the following medications within the past two months?

Aspirin, Bufferin, Anacin Tranquilizers

Blood pressure pills Weight reducing pills

Cortisone Blood thinning pills

Cough medicine Dilantin

Digitalis Allergy shots

Hormones Water pills

Insulin or diabetic pills Antibiotics

Iron or blood medications Barbituates

Laxatives Phenobarbital

Sleeping pills Thyroid medicine

Other medications not listed _____

Have you taken any non-prescription medications or drugs in the past two weeks?

Name what for? Dose/frequency last dose

1

2

3

Do you currently or have you ever had any of the following medical disorders?

Heart attack Yes ____ No ____

Chest pain Yes ____ No ____

Hardening of the arteries Yes ____ No ____

Irregular heart beat Yes ____ No ____

Kidney disease Yes ____ No ____

Diabetes Yes ____ No ____

Cancer Yes ____ No ____

Gout Yes ____ No ____

Asthma Yes ____ No ____

Epilepsy or seizure disorder Yes ____ No ____

Migraine headaches Yes ____ No ____ if yes, frequency/intensity ____

Psychiatric disorder Yes ____ No ____ if yes, what diagnosis _____

List the name of any diseases, illnesses or accidents you have had which required hospitalization. _____

Serious illnesses you have had not requiring hospitalization. _____

Do you have any other chronic illnesses or disabilities? _____

Do you play any type of musical instruments?

Yes ____ No ____ if yes, what and for how long? _____

What is your typing speed? ____ wpm

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