EXAMINING THE INDEPENDENCE AND CONTROL OF THE FINGERS

EXAMINING THE INDEPENDENCE AND CONTROL OF THE FINGERS:

EFFECT OF EXTRINSIC FINGER FLEXOR AND EXTENSOR INTERCONNECTION ON FORCE AND MUSCLE ACTIVITY DURING ISOMETRIC CONTRACTION

By

KIA SANEI, B.Sc.

A Thesis

Submitted to the School of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree

Master of Science

McMaster University

MASTER OF SCIENCE (2011) McMaster University
(Kinesiology) Hamilton, Ontario

TITLE: Examining the Independence and Control of the Fingers

AUTHOR: Kia Sanei, B.Sc. (McMaster University)

SUPERVISOR: Dr. Peter Keir

NUMBER OF PAGES: ix, 78

ABSTRACT

Biomechanical and neural factors have both been suggested to contribute to the limited independence of finger movement and involuntary force production. The purpose of this study was to evaluate the degree of finger independence by examining the activity of the four compartments of extensor digitorum (ED) and flexor digitorum superficialis (FDS) using surface electromyography and involuntary force production in the non-task fingers using methods such as the "enslaving effect" (EE) and the "selectivity index" (SI). Twelve male participants performed a series of 5-second sub-maximal exertions at 5, 25, 50 and 75% of maximum using isometric isotonic and ramp finger flexion and extension exertions. Ramp exertions were performed from 0 to 85% of each finger's maximum force with ascending and descending phases taking 4.5 seconds each with 0.5 seconds of plateau at 85%. Lower EE and higher SI (more selective force production) was found in flexion exertions compared to extension partially due to the higher activity of the antagonist ED compartments counterbalancing the involuntary activation of the non-task FDS compartments. Minimal FDS activity was seen during extension exertions. At forces up to and including 50%, both EE and muscle activity of the non-task compartments were significantly higher in descending exertions than the isotonic or ascending exertions. The selectivity index was also lower during the descending flexion and extension exertions at 25 and 50% MVC exertions. Up to mid-level forces, both finger proximity and contraction mode affects involuntary force production and muscle activation while at higher forces only finger proximity (and not the exertion mode) contributes to finger independence. The fingers were less selective at higher exertion levels (75% MVC) and all 3 exertion modes resulted in similar SI at 75% MVC in all flexion and extension exertions.

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor Dr. Peter Keir. I have benefitted from his guidance and supervision since the last year of my undergraduate studies at McMaster university. He has always been patient and considerate. His confidence in my abilities has allowed me to gain knowledge and experience throughout this project while directing me down all the right paths whenever I needed help.

I am also thankful for the support of my lab mates Mike Holmes, Joanne Hodder, Aaron Kociolek, Justin Weresch and Samantha Ebata. Each of these individuals has helped me at different stages of this project. I am very appreciative of my experience with them in the lab and their friendship.

I am grateful to John Moroz for his creative input in the design of my experimental setup. I would also like to acknowledge Joshua Cashaback for his help with the experimental collection program and Jimmy Tat for his help with data analysis and organization.

I would especially like to thank my parents (Mahrokh and Manouchehr) for always being there for me and believing in me. They have supported me each and every step of the way and guided me throughout the different stages of my life. I would also like to thank my brothers (Sina and Pouya) for their love and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 – INTRODUCTION

The human hand is capable of movements in which one or more fingers can move independently of the movement or posture of the other fingers. This ability is impressive when one considers the complex musculature of the extrinsic extensors and flexors of the fingers. The extrinsic finger flexor and extensor muscles have been considered as four separate muscles, each acting on one finger (Kilbreath and Gandevia, 1994), or one multi-digit muscle comprised of four anatomical or functional compartments (or subdivisions) serving individual fingers (Danion et al., 2002). Since many extrinsic and intrinsic hand muscles insert on each digit, the problem of multiple, and potentially redundant, degrees of freedom adds to the complexity of the control of finger movements (Valero-Cuevas, 2009). Although the complex apparatus of the hand has the ability to control fine movements and forces at individual fingers, the digits do not move completely independently even during more sophisticated tasks such as typing and piano playing. When human subjects are asked to move a finger, or apply force voluntarily with a finger, movement and force occur at other fingers as well (Schieber and Santello, 2004).

Mechanical and neural factors both contribute to the limited independence of finger movement and involuntary force production. It has been suggested that the interconnection between the extensor tendons, called juncturae tendinum (Kaplan, 1959), transmit tension and cause mechanical restrictions resulting in less independent finger movement and involuntary force production in the unintended fingers (von Schroeder et al., 1990; Zatsiorsky et al., 2000; Keen and Fuglevand, 2003; Leijnse et al., 2008b). Similar connections have been suggested to exist in the deep finger flexors (Kilbreath and Gandevia, 1994).

In addition to physical interconnections, neural restrictions in the form of synchronous firing of motor units in different compartments of the extrinsic extensor and flexor muscles (Keen and Fuglevand, 2004; Reilly et al., 2004) and multi-digit motor units in which muscle fibres of different compartments (that insert on tendons of adjacent digits) are innervated by the same motor unit (Zatsiorsky et al, 2000) have been suggested to contribute to limited finger independence. Furthermore, substantial overlap of the cortical territories associated with adjacent digits also contributes to the inability to exclusively exert force by individual fingers (Schieber and Hibbard, 1993; Slobounov et al. 2002b).

Several methods, such as the "enslaving effect" (Zatsiorsky et al., 1998) and a "selectivity index" (Keen and Fuglevand, 2003), have been used to quantify the involuntary force production. Zatsiorsky et al. (2000) examined the force production by the "slave finger" (i.e. the uninvolved finger) during maximal flexion exertions at the distal phalanges, distal and proximal interphalangeal joints (DIP and PIP respectively) using one finger or a combination of 2, 3 and 4 fingers. The enslaving effect decreased from the neighbouring fingers to the non-neighbouring fingers and ranged from 2 to 57% of the maximal finger force during single finger exertions. The enslaving effect was approximately symmetrical meaning that for example, the influence of the middle finger on the index finger was the same as the influence of the index finger on the middle finger (Zatsiorsky et al., 2000; Reilly and Hammond, 2000). Keen and Fuglevand (2003) used the selectivity index to reflect involuntary force production in the fingers during weak electrical stimulation of ED compartments. A selectivity index of 1.0 represents force produced in a single finger, while 0 represents and even distribution between all fingers. Overall, the selectivity index for all stimulation sites was 0.7 indicating relatively high selectivity of the ED compartments in producing force in only one digit. The ED compartment of the little finger had the highest selectivity index of 0.99, indicating an almost exclusive force production on digit 5.

The enslaving effect was further investigated in sub-maximal force levels of 10 and 30% MVC in finger flexion exertions by Danion et al. (2002) using a setup similar to Zatsiorsky et al. (2000). They found similar patterns of enslaving effects in flexion exertions using a combination of fingers between the two force levels. Danion et al. (2002) also recorded the activity of the flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP) and extensor digitorum muscles using surface EMG. Since only one pair of electrodes was used to record the activity of the extrinsic finger flexors, the activity of the FDS and FDP muscles were indistinguishable. However, the authors assumed that the FDS was active during exertions at the PIP joint, while FDP was active during the exertions at the DIP joint, based on a mathematical model by Li et al. (2000). Furthermore, since the activity of the compartments of the extensors and flexors were not recorded separately, direct relationship between the activity of the compartments of ED and FDS serving the same digit cannot be determined from this study. Flexor activity was significantly higher (at 10 and 30% MVC) during exertions of the ring finger. Although not confirmed with ultrasound or other imaging methods, the authors attributed the higher flexor activity during force production with the ring finger involved to more superficial flexor fibres of the ring finger compared to the other digits and as a result significantly higher EMG activity was recorded.

A number of studies have investigated the enslaving effects and forearm muscle compartment activity during ramp exertions of different fingers. In some of these studies, the enslaving effect was only analyzed during the constant phase that followed the ramp exertion and not during the ramp exertion itself (Slobounov et al. 2002a,b). Other studies have focused primarily on the accuracy of the force being exerted by one finger or a combination of all four fingers simultaneously (expressed as the variance from the target force) as opposed to the enslaving effect of single finger exertions (Shim et al., 2005; Valero-Cuevas, 2000). Compartment activities have been investigated using indewelling EMG during the ramp-up and ramp-down phases of the triangular ramp exertions; however, activities were recorded from muscular compartments serving only one digit (Maier and Hepp-Reymond, 1995a,b; Valero-Cuevas, 2000). Therefore, an extensive investigation of the effects of different types of exertions (ramp-up, ramp-down and constant force) on muscular compartment activity and enslaving effects is required to improve the understanding of neural and mechanical mechanisms involved in finger control.

Much of the research on the topic of finger independence has focused on force transmission between tendons of adjacent compartments and co-activation of different compartments of the extrinsic muscle (e.g. extensor digitorum) with little focus on the activity of the antagonist muscles. Co-activation of the antagonist muscular compartments may contribute to joint stability during isometric force production and counter balance the effect of the involuntary activations of the agonist compartments (Li et al., 2000). Even at low levels of force, the deep flexors of the fingers have shown to be active during extension of certain fingers (Reilly and Schieber, 2003). Therefore, assessment of the activity of the antagonist muscles during finger flexion or extension exertions would be beneficial in understanding the role of the antagonists in stabilizing the non-intended fingers and minimizing the involuntary force production in the uninvolved compartments of the extrinsic muscles (Schieber and Santello, 2004).

1.1. Purpose

The objectives of this thesis were to:

1. evaluate the degree of independent finger force production using
   a. enslaving phenomenon
   b. selectivity index

2. evaluate the activity of the four compartments of extensor digitorum (ED) and flexor digitorum superficialis (FDS) serving digits 2, 3, 4 and 5 using surface EMG during isometric isotonic and ramp finger flexion and extension exertions
   a. assess the common signal between ED and FDS compartments using the cross-correlation function

1.2. Hypotheses

1. The enslaving effect would increase with the increase in the isometric contraction force level.
   a. The adjacent fingers of the task finger would produce higher involuntary force compared to the non-adjacent fingers.
2. The uninvolved muscular compartments would be activated and the activity of these non-task compartments would increase with increasing level of force.
   a. The adjacent compartments (of the task compartment) would have higher activity compared to the non-adjacent compartments.

3. Both the enslaving forces and the compartment activities depend not only on the proximity of the non-task finger to the task finger, but also on the type of exertion.
4. The antagonist compartments would be co-activated to minimize the enslaving forces and the co-contraction of the antagonist compartments would increase with increasing level of force.

CHAPTER 2 – REVIEW OF LITERATURE

2.1. Anatomy

The digits of the hand are numbered from 1 (thumb) to 5 (little finger). The extrinsic finger muscles, or the compartments of flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), extensor digitorum (ED) are labeled from 2-5, representing each digit. The complete finger function also involves the intrinsic muscles of the hand (located in the palm).

2.1.1. The Extrinsic Finger Flexors

Flexor digitorum superficialis (FDS) muscle has two proximal attachments: one on the medial epicondyle of humerus and the other on the superior and anterior border of radius. The four compartments of FDS give rise to four tendons distally, which go through the carpal tunnel and insert on the middle phalanges of digits two to five. The function of the FDS is to flex the digits at the proximal interphalangeal (PIP) joints, metacarpophalangeal (MCP) joint and to flex the wrist joint. The median nerve innervates FDS.

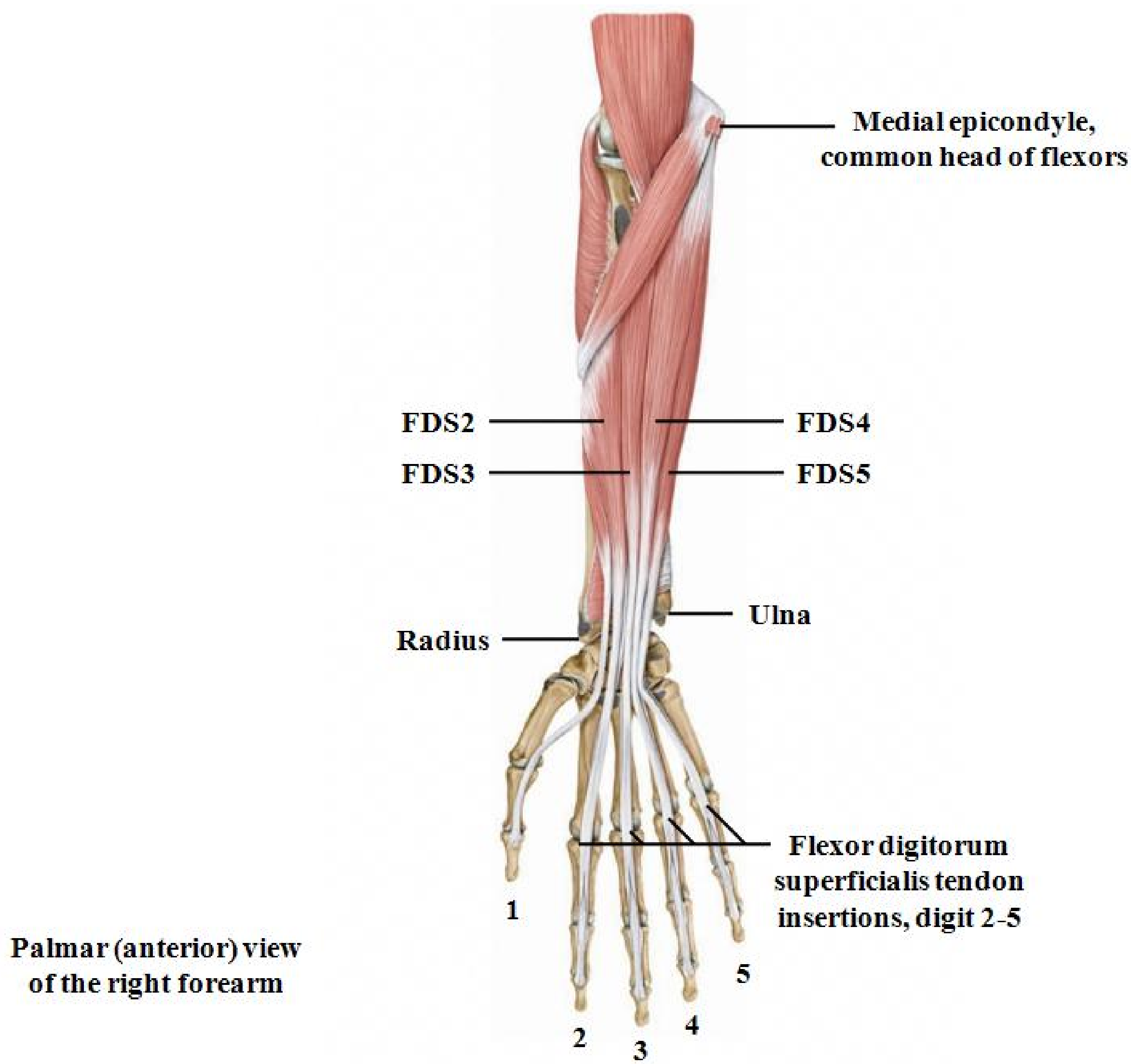


Figure 2.1. Palmar view of the forearm showing the 4 compartments of the FDS gives rise to 4 tendons serving digits 2 to 5. Figure taken from Shuenke et al. (2006).

Flexor digitorum profundus (FDP) attaches proximally to the anterior medial surface of the ulna (Tortora and Grabowski, 2003) and interosseous membrane. FDP3-5 arise from the ulna while FDP2 originates more distally from the interosseous membrane (Kilbreath and Gandevia, 1994). FDP gives rise to four external tendons, which pass through the carpal tunnel deep (dorsal) to the FDS tendons and attach to the base of the distal phalanges of the digits. The four tendons of FDS along with the four tendons of FDP are enclosed in a common flexor synovial sheath as they pass through the carpal tunnel. The specific action of FDP is to flex distal interphalangeal (DIP) joint. The FDP also crosses and flexes the PIP, MCP and wrist joints. The median nerve innervates the lateral compartments of the muscle (FDP2 and FDP3) while the two medial compartments (FDP4 and FDP5) are innervated by the ulnar nerve.

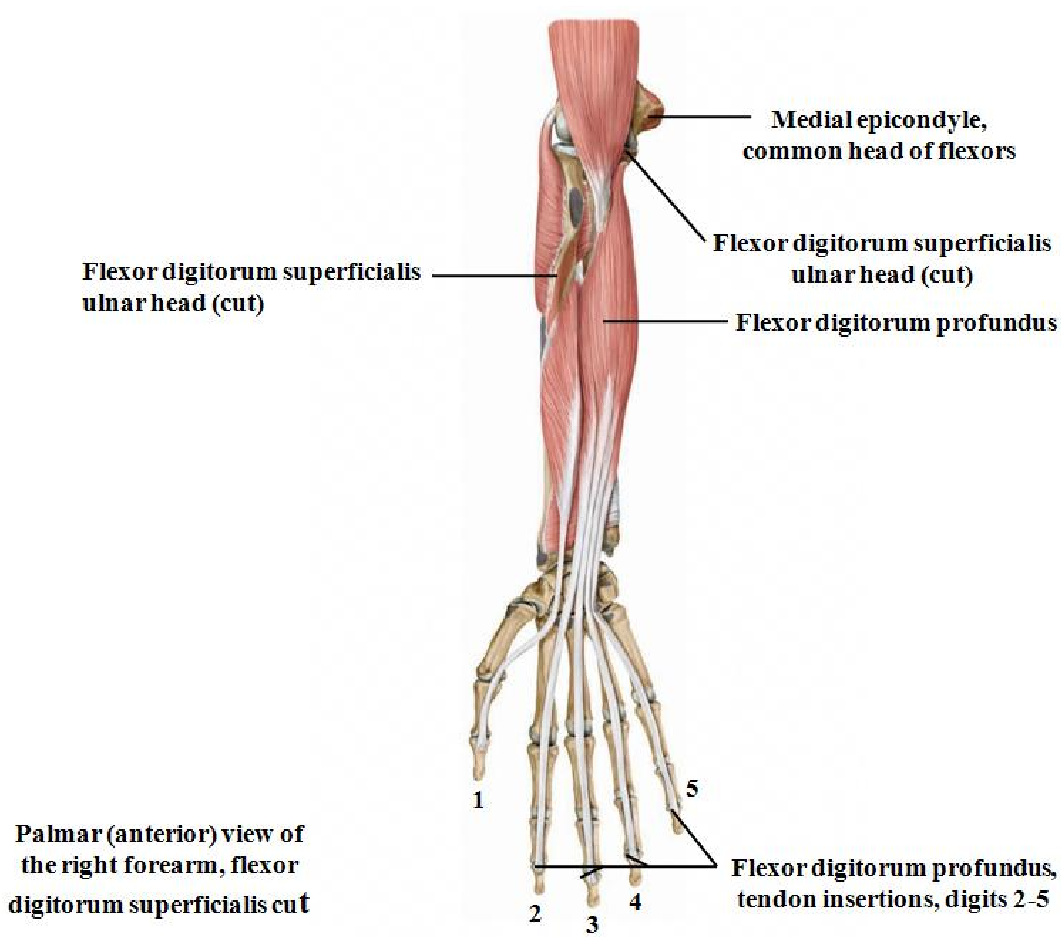


Figure 2.2. Deep view of the ventral forearm (FDS has been removed). FDP serves digits 2 to 5. Figure taken from Shuenke et al. (2006).

2.1.2. The Extrinsic Finger Extensors

Extensor digitorum communis (ED) is the principle extensor of digits two to five at the MCP, DIP and PIP joints (Tortora and Grabowski, 2003). ED originates to the lateral epicondyle of humerus and gives rise to four tendons that pass through a common synovial sheath deep to the extensor retinaculum on their way to inserting on the middle and distal phalanges. The extensor tendons are connected in the dorsum of the hand by juncturae intertendinei proximal to the MCP joint (Kaplan, 1959; Leinjse et al., 2008a). It has been suggested by von Schroeder et al. (1990) that the juncturae intertendinei (also known as juncturae tendinum) has several functions including redistribution of force, stabilization of the MCP joints, coordination of digit extension and spacing of the ED tendons. Juncturae intertendinei are thought to be at least partially responsible for the inability to voluntarily extend fingers independently (Kaplan, 1959; Keen and Fuglevand, 2003; Leinjse et al., 2008a). ED is innervated by the deep branches of the radial nerve (C6-C8).

Extensor indicis (EI) and extensor digiti minimi (EDM) are the other two extrinsic finger extensor muscles, which extend the index and little fingers, respectively. EI originates from the dorsal surface of the distal half of the ulna and inserts on the middle phalanx of the index finger and ED2. EI extends all the joints of the index finger (digit 2). EDM originates from the common extensor tendon (off the lateral epicondyle) and inserts to the tendon of ED5 at the proximal phalanx of the little finger. EDM extends all the joints of digit 5 (“little” finger). EI is innervated by the deep radial nerve while EDM is innervated by the posterior interosseous branch of the deep radial nerve.

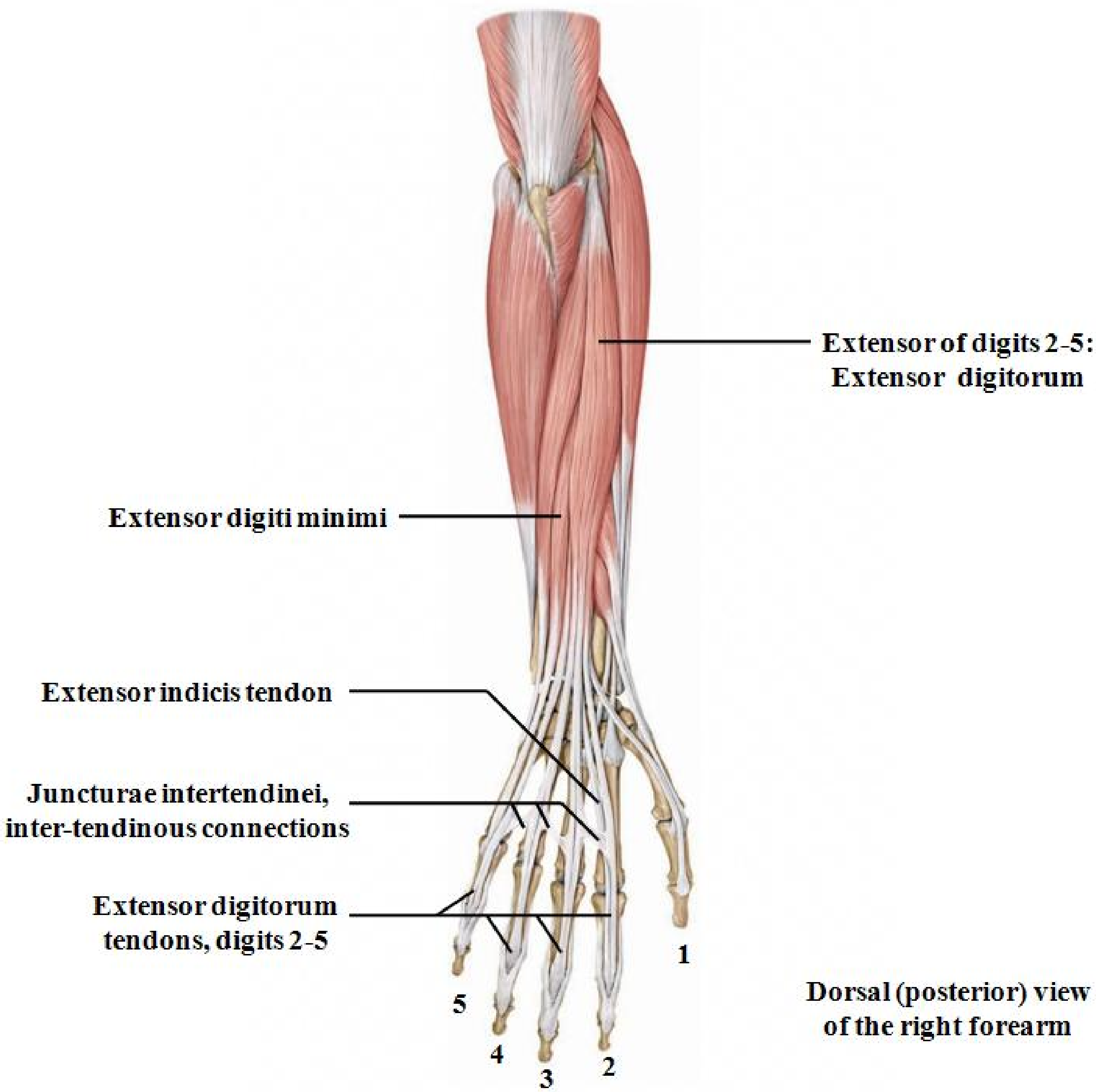


Figure 2.3. Dorsal view showing ED and other extensor muscles of the forearm. ED gives rise to 4 tendons serving digits 2 to 5. Also shown are EI and EDM. The tendons of ED are connected on the back of the hand by the juncturae intertendinei. Figure taken from Shuenke et al. (2006).

2.2. Muscle Activity

The slender build and the close proximity of the multi-digit extrinsic finger extensors and flexors as well as other muscles of the forearm present some difficulties in recording the activity of these muscles using surface EMG (Leinjse et al., 2008a). In order to minimize crosstalk between the electrodes, indwelling electrodes have been used to study the activity of individual compartments of ED (Keen and Fuglevand, 2003; 2004a and b), FDS (McIsaac and Fuglevand, 2007) and FDP (Schieber et al., 2001; Kilbreath et al., 2002; Reilly et al., 2004). Although indwelling EMG has been used to record EMG from these muscles, movement of electrodes during dynamic contraction and the invasiveness of this method have been suggested to be some of the drawbacks of wire electrodes (Mogk and Keir, 2003). Also, the use of indwelling EMG does not completely eliminate crosstalk between electrodes. Burgar et al. (1997) found significant crosstalk in some of their subjects (using fine wire electrodes) between FDS and FDP muscles as well as FDS2 and FDS3 compartments during weak flexion exertions of the index finger.

The cross correlation function is the most common method of quantifying the amount of common signal present between the recorded activities of neighbouring muscles (Mogk and Keir, 2003). The cross correlation function correlates two different time series data such as EMG signals and indicates the size of the correlation as a function of the time lag between the two signals (Winter and Patla, 1997). This method has been used to determine the amount of common signal in the forearm during static and dynamic tasks (Mogk and Keir, 2003; Leinjse et al., 2008b). Mogk and Keir (2003) placed bipolar surface electrodes (1 cm diameter) around the circumference of the forearm with centre to centre spacing of 3 cm between the electrode pairs to determine the amount of common signal (or crosstalk) during pinch and grip tasks. The amount of common signal was less than 42% between the adjacent electrode pairs and no more than 11 % between the electrode pairs spaced 6 cm apart. The common signal between the electrodes placed on the flexor and extensor side of the forearm was less than 2%. Although the electrodes were not placed on specific muscles, except for the landmark electrodes placed on flexor carpi radials muscle, this finding suggests that when the activity of both the flexors and the extensors are recorded using surface EMG during pinch and grip tasks, the activity recorded from the antagonists could be attributed to co-activation rather than crosstalk.

Leijnse et al. (2008a) dissected fifteen forearm specimens in order to determine the optimal location for surface electrodes on the forearm extensor muscles including the compartments of ED. In a follow up study, Leijnse et al. (2008b) used these results to assess the activity of the ED compartments using small (4 mm) surface electrodes during a tapping task with the wrist in neutral posture and the non-performing fingers resting on a surface. Two methods were used to evaluate crosstalk and co-activation. The first method used a ratio of the EMG from the ED compartment serving the task finger ("primary" EMG) to the EMG from all other ED compartments ("accessory" EMG) to quantify the relative activity of each of the uninvolved compartments. The mean of peak EMG of 10 consecutive taps (chosen based on amplitude consistency) was calculated for each electrode pair. The second method used the Pearson correlation coefficients to correlate the mean peak EMG between the electrode pairs (for example, ED2 and ED3) across the subjects. Although neither method differentiates between crosstalk and co-activation, the authors attributed the recorded accessory EMG mainly to crosstalk or co-activation depending on the anatomical proximity of the compartments (if the compartments are in close proximity, accessory EMG is mainly crosstalk between electrode pairs). As an example, the accessory EMG of ED2 and ED4 during tapping of digits 4 and 2, respectively, were interpreted as crosstalk due to close anatomical proximity. This assumption may not be completely accurate since co-activation between the compartments of ED has been reported during low force isometric extension of all four fingers (Keen and Fuglevand, 2004). ED2 electrodes recorded 53% accessory EMG with a moderate correlation coefficient (0.59) during tapping of digit 4. ED4 had 30% accessory EMG during tapping of digit 2 and was weakly correlated with ED2 ($r = 0.22$). Tapping of the second digit resulted in co-activation of ED2 and EI. ED5 was not targeted since the ED5 muscle belly is not always anatomically separable from the muscle belly of ED4 (Leijnse et al., 2008a).

In summary, electrode spacing of 3 cm (or less) has been shown to minimize the amount of crosstalk between the adjacent electrode pairs (Mogk and Keir, 2003). Furthermore, the activity of the slender extrinsic superficial finger flexors and extensors could be evaluated with reasonable accuracy using the cross correlation function (Mogk and Keir, 2003) or the correlation coefficient calculated between each electrode pair (Leijnse et al., 2008b). The interpretation of the results is the same using either of these methods since the cross correlation function is the correlation coefficient calculated on two time series like EMG signals.

2.3. Independent Movement of Fingers

2.3.1. Mechanical restrictions of extrinsic finger flexors and extensors

It has been widely reported that mechanical restrictions due to interconnections between the distal tendons of the extrinsic finger flexors (tendons of FDP) and the distal tendons of the extensors (tendons of ED) may be at least partially responsible for the limited independent movement of digits in flexion and extension (Zatsiorsky et al., 2000; Schieber et al., 2001; Danion et al., 2002; Kilbreath et al., 2002; Keen and Fuglevand, 2003; Reilly et al., 2004).

Keen and Fuglevand (2003) investigated the extent of force transmission between compartments of ED during weak electrical stimulation of ED. They inserted electrodes in different parts of ED from proximal to distal and from radial to ulnar. A "selectivity index" was calculated as a measure of force distribution between the four fingers. A selectivity index of 1 represents force produced in one finger only and 0 represents force evenly distributed between all fingers. They found the selectivity index to be significantly smaller in the middle section of the forearm compared to the proximal and distal sites (the selectivity index value of 0.59 in the middle of the muscle compared to 0.75 and 0.8 at the proximal and distal sites respectively). On average, the selectivity index for all sites (of electrical stimulation) was 0.7 indicating relatively high selectivity of the ED muscle in force production on one digit. The sites that produced force primarily on the little finger had significantly higher selectivity index (0.99 indicating almost exclusive force production on digit 5) than the other fingers. The results of this study suggest that the juncturae tendinum played minimal role in inter-compartment force distribution of ED.

In a study of the macaque (monkey) finger flexor musculature, Schieber et al. (2001) evaluated active and passive force transmission in FDP. Using the same measure of force transmission as Keen and Fuglevand (2003), the selectivity index, they measured the fraction of total tension on each tendon. Stimulation of branches of the median and the ulnar nerve innervating different compartments of the FDP muscle resulted in low selectivity indices of 0.3 to 0.35, indicating that force was distributed across multiple macaque FDP tendons. Tension distribution between the macaque FDP tendons was far greater than those observed in human ED (0.3-0.35 compared to 0.7, higher selectivity index value indicates smaller force transmission) when the primary nerve branch was stimulated compared to intramuscular stimulation studied by Keen and Fuglevand (2003). The benefit of the animal model was that the passive tension transmission via tendon interconnections was also investigated by pulling at different radio-ulnar locations of the FDP tendon just proximal to the wrist. These invasive techniques are not possible in vivo. Although passive tension produced force primarily on one distal phalanx, tension was also observed in the adjacent distal phalanges.

Another method of evaluation of the involuntary production of force in the "non-intended" fingers was investigated in finger flexion exertions and termed an "enslaving effect" by Zatsiorsky et al. (1998). Participants exerted maximal flexion force at the distal interphalangeal joint using one finger or a combination of 2, 3 and 4 fingers while force was recorded for each finger. The force produced by the "slave finger" (uninvolved finger) was expressed as a percent of the maximum force produced by this finger in the single finger maximal exertion trial. The results showed that the uninvolved fingers produced forces ranging from 11 to 52% of the maximal finger force. The enslaving effect decreased from the neighbouring fingers to the non-neighbouring fingers. Also, "force deficit" was observed when more than one finger was involved in the maximal exertions meaning that the peak forces of the individual fingers during these exertions were smaller than their maximal forces during the single finger maximal exertions. The enslaving effect was approximately symmetrical meaning that the influence of the middle finger on the index finger was the same as the influence of the index finger on the middle finger. In this specific example, the middle finger produced 27.7% of its maximal force during the maximal exertion of the index finger while the index finger produced 27.6% of its maximal force during the maximal exertion of the middle finger. The reciprocal non-instructed force production between pairs of fingers during sub-maximal flexion exertions (40, 60 and 80% MVC) with the distal phalanges has also been reported by Reilly and Hammond (2000). Interestingly, the amount of force production in the non-intended fingers is not significantly different between the dominant and non-dominant hands (Reilly and Hammond, 2000).

The enslaving effect was further investigated in sub-maximal force levels of 10 and 30% MVC in finger flexion exertions by Danion et al. (2002). They recorded the activity of the FDS, FDP and ED using surface EMG during flexion exertions using one finger or a combination of 2, 3 and 4 fingers at the distal and proximal interphalangeal joints. Electrode placement did not distinguish between FDS and FDP muscle activities but they assumed that FDS was active in PIP flexion while FDP was active in DIP flexion. They based this assumption on the mathematical model of Li et al. (2000). Although FDP contributed mainly to force production in the distal phalanges based on their model, it also contributed to moment production at the PIP joint. As an example, FDS2 force increased 39% when force was produced at the DIP joint compared to force production at the middle of the distal phalanx. Force production at the middle of the distal phalanx in digit 2 resulted in estimated FDP force of 102 N and FDS estimated force of 154 N. Therefore, the assumption that the activity recorded with surface EMG is isolated to either FDS or FDP is not valid.

Danion et al. (2002) found similar patterns enslaving effects in flexion exertions using a combination of fingers (2, 3 and 4 fingers contributed to force production) between 10 and 30%

MVC. Flexor activity was significantly higher (at 10 and 30% MVC) during the tasks that force was produced with any combination of fingers that involved the use of digit 4. Although not confirmed with ultrasound or other imaging methods, the authors attributed the higher flexor activity during force production with digit 4 involved to more superficial digit 4 flexor fibres compared to the other digits and as a result significantly higher EMG activity was recorded. The activity of the antagonist finger extensor muscle (ED) was also recorded using surface EMG. The authors found no significant correlation between the extensor and flexor activities. Since only one pair of electrodes were used to record EMG from ED and one pair for the flexors, direct relationship between the compartments of ED and FDS serving the same digit cannot be determined from this study. It is likely that based on their electrode placement, the activity of FDS4 and ED3 were recorded. The activity of ED changed based on the finger combination but the authors did not report in which combinations the activity increased or decreased. Co-activation of the antagonist muscle may contribute to joint stability in isometric force production (Li et al., 2000). Although not tested in this study, the co-activation of the antagonist muscle may counter balance the effect of the involuntary force production in the uninvolved finger. Indeed, during weak extension exertions (5% MVC), Reilly and Schieber (2003) reported activity in the compartments of FDP adjacent to the finger producing the extension force (they did not report the amount of activity).

Slobounov et al. (2002a) also investigated enslaving effects during sub-maximal fingertip flexion exertions. A ramp-up phase was used prior to constant force production with duration of 0.5, 1 and 1.5 seconds corresponding to 25, 50 and 75% MVC respectively. However, the enslaving forces were only analyzed during the plateau phase. The ramp-up portion of the exertion was only analyzed to quantify the accuracy of force production by individual fingers. Similar patterns of enslaving effect were observed in the sub-maximal exertion versus the previous findings of Zatsiorsky et al. (1998) during maximal exertions with the index finger being the most independent and ring finger being the least independent. However, the absolute enslaving forces where highest in the ring finger during the little finger exertions. The conclusion that the ring finger was the least independent during fingertip flexion exertions was based on the sum of enslaving forces of all fingers during ring finger exertions and not the absolute effect of the ring finger on any individual finger (i.e. little finger). Interestingly, the reciprocity of enslaving effect between pairs of fingers which was previously reported by Zatsiorsky et al. (1998) during maximal and Reilly and Hammond (2000) during sub-maximal exertions of the distal phalanges (greater than 40% MVC) did not occur at the lowest force level of 25% MVC.

2.3.2. Neural Factors

It has been reported that even surgical excision of the juncturae tendinum did not improve the independence of finger extension in musicians (Kaplan, 1959) leading researchers to examine neural limitations (Keen and Fuglevand, 2004; Kilbreath et al., 2002; Reilly et al., 2004; McIsaac and Fuglevand, 2007). Keen and Fuglevand (2004) had participants maintain a weak isometric extension exertion while single motor unit activity was recorded with two microelectrodes inserted into the target compartments of ED. Synchronous firing of motor units was determined using a cross correlation histogram with one electrode acting as a reference. Motor unit synchrony was defined as the peak at time zero of the cross correlation histogram. Synchronous firing of the motor units was greatest when the two electrodes were in the same compartment of

ED compared to between compartments. Synchronous firing between the compartments of ED could explain the involuntary movement of the neighboring finger when individual finger extension movement is desired. Synchronous firing of motor units was highest in the neighboring compartments of the ED4 and lowest in the neighboring compartments of ED2. These results suggest that extension of the ring finger is least independent and extension of the index finger is most independent.

The extent of independent flexion of the DIP joint was investigated by Kilbreath and Gandevia (1994). The activity of all four FDP compartments were recorded using bipolar intramuscular wire electrodes during individual flexion of the DIP joint at force levels ranging from 2.5 to 50% MVC. Participants lifted weights by flexing the DIP joint of one finger while the other digits were relaxed and the PIP joint of the involved finger was immobilized. Flexion of the DIP joint with a force equal to 5% MVC or more (of the FDP compartment) resulted in co-activation of the adjacent FDP compartments. In order to investigate the mechanical properties of the FDP muscle the arm was anesthetized (and paralyzed) distal to the elbow using blood pressure cuff while the distal phalanx was moved passively. There was no movement in the other digits suggesting that in passive movement of a “relaxed” muscle, force is not transmitted to the adjacent digits by friction or tight linkage between tendons. They did not eliminate the possibility of mechanical interactions between the FDP compartments during active movement based on two observations. First, passive movements of the distal phalanges adjacent to the test finger were observed occasionally even in the absence of FDP activity in these adjacent compartments. Second, based on examination of 9 cadaver forearms, the authors found tendinous slips joining the adjacent tendons of FDP in the distal forearm. Also, the muscle bellies of the 4 compartments of FDP were not completely separated. Leijnse (1997) reported that even when the connections between the tendons of the FDP compartments were removed surgically in a patient, involuntary force production in the distal phalanges was observed. This finding suggests that force transfers are likely the result of co-activation of the FDP compartments, connections between the muscle bellies of the FDP compartments or a combination of the two.

In a more recent study, Kilbreath et al. (2002) investigated the degree of selectivity of the motor units of FDP in producing force on one finger. They measured the activity of the FDP compartments using intramuscular wire electrodes while participants weakly exerted force (< 2% MVC of fingertip force) on a cylinder with force sensors under each fingertip. Motor units of digits 2, 3 and 4 of the FDP muscle were selective in force production (majority of the force produced under the respective finger). More than half of the motor units of digit 5 (8 out of the 14 motor units examined) produced significant force in the neighboring ring finger (up to 62% of the force). These results suggest that the motor units of FDP5 may produce force in the adjacent FDP4 fibres.

Reilly et al. (2004) studied motor unit synchronization using two bipolar fine-wire electrodes inserted into compartments of the FDP muscle during weak flexion exertions at the distal phalanges. The synchronous firing of the motor units was quantified by the discharge times of the motor units recorded using cross-correlation histogram with a period of 100 ms before and after discharge time of the reference motor unit. Significantly higher synchronization was observed in FDP4 and FDP5 compared to FDP2 and FDP3. This finding may explain the results of Reilly and Hammond (2000) and Kilbreath et al. (2002) who showed significant force production in the ring finger when the participants were instructed to exert flexion force with the little finger. Higher synchronous firing was observed in the units corresponding to adjacent fingers compared to the units of the non-adjacent fingers. A similar pattern was also reported by Keen and Fuglevand (2004) in the ED muscle. This pattern of motor unit synchrony could explain the higher enslaving effect (involuntary force production) in neighbouring fingers compared to the non-adjacent fingers reported by Zatsiorsky et al. (1998).

The synchronous firing in the motor units of the FDS muscle during weak flexion exertions at the proximal interphalangeal joint was investigated by McIsaac and Fuglevand (2007). They recorded the motor unit activity by inserting 2 fine wire electrodes in the FDS muscle. Motor unit synchrony was quantified by an index calculated from the cross correlation histogram. The cross correlation histogram was constructed from 100 ms before to 100 ms after the discharge of the reference unit with bin widths of 1 ms. The index was calculated as the ratio of the counts in the histogram peak to the counts in the first and last 60 ms of the histogram. Similar to Keen and Fuglevand (2004) and Reilly et al. (2004), the synchronous firing of the motor units was greatest when the 2 electrodes were in the same compartment of FDS. Motor unit synchronization between compartments was lower in the FDS muscle than the FDP muscle (Reilly et al., 2004). Synchrony was higher between ED3-ED4 and ED4-ED5 (Keen and Fuglevand, 2004) than the motor units of the finger flexor compartments suggesting less independent movement of the middle, ring and little fingers in extension. These results support the findings of Robinson and Fuglevand (1999) that the least independent finger movement, in both extension and flexion, was the extension of the ring finger while the highest independence was observed in extension of the index finger.

2.4. Summary

In summary, the lack of independent finger movement is due to a combination of biomechanical and neural restrictions. Distal tendon interconnections of the extrinsic finger extensor as well as tendinous slips between the adjacent tendons of the deep finger flexors and their connections in the palm have been reported as possible contributors to the mechanical restrictions of independent finger extension and flexion. Neural factors that may be responsible for the lack of independent finger motion include common activation of different compartments and motor units innervating muscle fibres residing in multiple compartments. The extent to which multi-digit motor units result in force distribution to adjacent tendons of the extrinsic finger flexors and extensors versus synchronous firing of the motor units each acting on a single digit is the subject of active investigation (Schieber and Santello, 2004).

CHAPTER 3 - MANUSCRIPT

Independence and Control of the Fingers Depends on Contraction Direction and Mode

Kia Sanei and Peter J. Keir*

Department of Kinesiology, McMaster University, Hamilton, Ontario, Canada

To be submitted to: *Journal of Electromyography & Kinesiology*

* Corresponding Author:
Peter J. Keir, PhD
Department of Kinesiology
McMaster University
1280 Main Street West
Hamilton, Ontario, L8S 4K1
Phone: (905) 525-9140 ext. 23543
Fax: (905) 523-6011
Email: pjkeir@mcmaster.ca

3.1. Abstract

Biomechanical and neural factors have both been suggested to contribute to the limited independence of finger movement and involuntary force production. The purpose of this study was to evaluate the degree of finger independence by examining the activity of the four compartments of extensor digitorum (ED) and flexor digitorum superficialis (FDS) using surface electromyography and involuntary force production in the non-task fingers using the "enslaving effect" (EE). Twelve male participants performed a series of 5-second sub-maximal exertions at 5, 25, 50 and 75% of maximum using isometric isotonic and ramp finger flexion and extension exertions. Ramp exertions were performed from 0 to 85% of each finger's maximum force with ascending and descending phases taking 4.5 seconds. Lower EE was found in flexion exertions likely due to the higher activity of the antagonist ED compartments counterbalancing the involuntary activation of the non-task FDS compartments. Minimal FDS activity was seen during extension exertions. At forces up to and including 50%, both EE and muscle activity of the non-task compartments were significantly higher in descending exertions than the isotonic or ascending exertions. Up to mid-level forces, both finger proximity and contraction mode affects involuntary force production and muscle activation while at higher forces only finger proximity contributes to finger independence.

Keywords – Finger Independence and Control; Enslaving Effect; Extensor Digitorum; Flexor Digitorum Superficialis; Surface EMG; Ramp Exertions

3.2. Introduction

The human hand is a remarkable system in which fingers can move independently or in complex synchrony. Independent movement is impressive considering the musculature of the hand. The extrinsic finger flexors (both deep and superficial) and extensors have been considered as four independent and separate muscles, each acting on one finger (Kilbreath and Gandevia, 1994), or a single muscle comprised of compartments (Danion et al., 2002). While there exists great control of fine movements and forces in individual fingers, the digits do not act completely independently even during more sophisticated tasks such as typing and piano playing. When human subjects are asked to move a finger or apply force voluntarily with a finger, movements and/or forces also occur in other fingers (Schieber and Santello, 2004).

Both mechanical and neural factors contribute to the limited independence of finger movement and involuntary force production. Tension may be transferred by interconnections between the extensor tendons (juncturae intertendinei) resulting in less independent finger movement and force production in other fingers (von Schroeder et al., 1990; Zatsiorsky et al., 2000; Keen and Fuglevand, 2003; Leijnse et al., 2008b). Similar connections have been suggested to exist in the deep finger flexors (Kilbreath and Gandevia, 1994). In addition to physical connections, neural restrictions have also been demonstrated including synchronous firing of motor units in different extrinsic extensor and flexor muscle compartments (Keen and Fuglevand, 2004; Reilly et al., 2004) and motor units innervating muscle fibres in compartments of adjacent digits (Zatsiorsky et al, 2000). Furthermore, there is substantial overlap of the cortical territories associated with adjacent digits that also contributes to the inability to exert force exclusively by individual fingers (Schieber and Hibbard, 1993; Slobounov et al. 2002b).

Involuntary finger force production has been quantified by the "enslaving effect" (Zatsiorsky et al., 1998) and the "selectivity index" (Keen and Fuglevand, 2003). Zatsiorsky et al. (2000) reported the force produced by a "slave", or uninvolved finger, was lower in non-neighbouring fingers and ranged from 2% to 57% of maximal finger force during single finger exertions. In general, the enslaving effect reciprocated between fingers (Zatsiorsky et al., 2000; Reilly and Hammond, 2000). Keen and Fuglevand (2003) used the selectivity index to reflect involuntary force production in the fingers during weak electrical stimulation of ED compartments. Overall, the selectivity index for all stimulation sites was 0.7 indicating relatively high selectivity of the ED to produce force in only one digit. A selectivity index of 1.0 represents force produced in a single finger while 0 represents and even distribution between all fingers.

Similar enslaving effect patterns have been reported for sub-maximal finger flexion exertions at 10 and 30% (Danion et al., 2002). They also reported muscle activity from two sites forcing the authors to assume the activity of the deep and superficial flexors based on a mathematical model (Li et al., 2000). Higher flexor activity during ring finger exertions was attributed to the ring finger muscle compartment being more superficial, although this was not confirmed.

Many studies have evaluated enslaving effects and/or compartmental muscle activity during steady state of sub-maximal flexion exertions with or without a preceding ramp exertion (Slobounov et al 2002a,b). Others have focused on the accuracy of the force exerted by one finger or by all fingers simultaneously (Shim et al., 2005, Valero-Cuevas, 2000). In these studies, muscle activity was recorded from a muscular compartment serving a single digit (using indwelling EMG) (Maier and Hepp-Reymond, 1995a,b; Valero-Cuevas, 2000). A thorough investigation of different types of isometric exertions (ramp-up, ramp-down and submaximal steady state) and their effects on compartment activity and enslaving effects is required to improve the understanding of neural and mechanical aspects of finger control.

Thus far, little focus has been placed on the antagonist muscles. Co-activation of antagonist muscle compartments would contribute to joint stabilization and counter balance the effect of the involuntary force production in the uninvolved fingers (Li et al., 2000). Even at low force levels, the deep finger flexors have been shown to be active during finger extension (Reilly and Schieber, 2003). Assessment of antagonist muscle activity during finger flexion and extension exertions would be beneficial in understanding their role in stabilizing the “non-target” fingers and minimizing involuntary force production in the other compartments of the extrinsic muscles (Schieber and Santello, 2004). The purpose of this study was to evaluate the activity of the four compartments of extensor digitorum (ED) and flexor digitorum superficialis (FDS) using surface EMG and the degree of independent finger force production by evaluating the enslaving phenomenon during isometric isotonic and ramp finger flexion and extension exertions. It was hypothesized that enslaving forces and muscle compartment activity would depend not only on the non-task finger proximity to the task finger, but also on the mode of exertion. It was also hypothesized that antagonist compartments would be activated in order to minimize the enlaving forces in the non-task fingers.

3.3. Materials and Methods

3.3.1. Participants

Twelve right-handed healthy male volunteers with no history of upper extremity musculoskeletal disorders participated (height, 177.5 ± 4.1 cm; mass, 78.9 ± 8.9 kg; age, 24.3 ± 2.8 years). The study protocol was approved by the McMaster research ethics board and all participants provided informed written consent.

3.3.2. Experimental Set-up

Fingers were placed in four adjustable padded metal rings each attached to a force transducer (MLP50, Transducer Techniques, Temecula, CA, USA) mounted on a vertical metal plate (Figure 1). Participants were seated upright with the right forearm and elbow stabilized on a table with padding. Table height was adjusted to approximate 120° of elbow flexion with the shoulder at 0° of abduction. Splinting material (Dynacast, BSN Medical Inc., Laval, QC, Canada) was used to firmly secure a mid-prone forearm with a neutral wrist (Figure 3.1).

****

Figure 3.1

****

3.3.3. Experimental Conditions and Procedure

Participants performed a series of static finger flexion and extension exertions at several force levels while EMG and force were recorded from all four digits. Surface EMG was collected using bipolar reusable surface electrodes with a fixed centre-to-centre electrode distance of 2 cm (Biometrics Ltd., Gwent, UK). Standard electrode preparation was followed, including shaving and cleaning the skin with alcohol, placing the electrodes over the muscle belly along the fibre direction. Muscle activity was recorded from the 4 compartments of FDS (FDS2-5, for digits 2-5, starting from index), and ED (ED2-5). Electrodes for ED compartments were placed according to Leijnse et al. (2008b). Electrode placements for FDS were adapted from Perotto et al. (2004) and Burgar et al. (1997) with additional anatomical information from Shuenke et al. (2006). A summary of electrode locations has been presented in Table 3.1. The ED5 muscle belly is not consistently distinguishable from extensor digiti minimi (EDM), thus activity recorded was likely a combination of both muscles (Leijnse et al., 2008a, van Duinen et al. 2009). Detailed anatomical and functional testing in addition to monitoring EMG, confirmed electrode placement.

****

Table 3.1

****

Participants performed a series of maximal voluntary contraction (MVC) trials. Trials were 5 seconds in duration with 1 minute of rest between trials. Each MVC trial was performed twice. In extension, MVCs were performed with single finger isometric exertions with the rings placed at mid-proximal phalanges (EXT). Two sets of MVCs were performed for individual finger flexion exertions with the rings placed around the middle (FLXp) and distal phalanges (FLXd). Prior to each trial, participants were told which finger would be exerting force, to keep their fingers straight, and to concentrate on exerting force with the task finger. MVC trials were repeated if the peaks differed by more than 5%. The highest force obtained in either MVC trial was used as the maximal force.

Participants then performed a series of sub-maximal isometric finger flexion and extension exertions at 5, 25, 50 and 75% MVC in the same conditions as the MVC trials (EXT, FLXp, FLXd). In each trial, participants exerted the target force with the task finger for 5 seconds, rested 5 s, then repeated the relative force with each successive finger until all fingers had completed that force level (Figure 3.2a). Thirty seconds of rest was given at the end of each trial. This was repeated three times for each force level. To avoid a potential order effect, 3 finger orders were used (2-3-4-5, 5-4-3-2 and 4-5-2-3). The force levels were performed in an increasing order (5 - 75%). In total, 12 trials were performed in each condition, EXT, FLXp and FLXd (4 force levels, 3 trials each). The order of exertion conditions (EXT, FLXp and FLXd) was randomized for each participant.

Following the constant force trials, a series of three isometric triangular (ramp) exertions were performed for each finger with the same conditions (EXT, FLXp and FLXd). During ramp exertions, participants increased from rest (0% MVC) to 85% MVC over 4.5 s, maintained for

0.5 s, then decreased to 0 in 4.5 s (Figure 3.2b). This was followed by 60 s rest. The finger order within each trial was the same pre-determined order as used during the sub-maximal exertions.

****

Figure 3.2

****

Force and EMG data were collected at 1000 Hz using a custom program (LabView 8.5, National Instruments, TX, USA). EMG was differentially amplified (CMRR > 96 dB, input impedance ~ 10^{15} Ω; Biometrics Ltd., Gwent, UK) and band pass filtered (20 Hz – 450 Hz). Analyses were performed using a custom Matlab program (V.7.6, The MathWorks, MA, USA).

3.3.4. Data Analysis

Raw EMG was full wave rectified and low pass filtered using a dual pass critically damped filter (second order, fc = 3 Hz) and normalized to maximum voluntary excitation (MVE). MVE was defined as the peak EMG for each muscle during the MVC trial. Force signals were low pass filtered using a second order dual pass critically damped filter with a cut-off frequency of 10 Hz then normalized to the MVC for each finger. The MVE for each FDS compartment was the highest value found in any of the MVC flexion exertions.

For each constant force trial, mean of the middle 3 s of the 5 s exertion was determined for normalized force and average EMG (AEMG). The 3 trials were averaged. The ramp exertion trials were split into ascending and descending phases. From the ascending and descending phases, the same 4 force levels were extracted (5, 25, 50, and 75%). The mean of a 50-ms window about each target force was calculated for each force and EMG channel. The enslaving effects (EE) were defined as the mean force produced by the non-task fingers during exertion of the task finger.

The dependent measures in this experiment were AEMG and EE. Due to a much slower rate of force during descending phase of the ramp exertion, the 5% MVC force level was often not attained during the analyzed time period, thus, the 5% MVC force level was not included in the statistical analysis (but it has been included in the results based on fewer samples). A series of 3 (exertion modes) × 3 (non-task fingers) factorial analyses of variance (ANOVA) were used to assess EE at each level of force (alpha = 0.05). The 3 exertion modes were isotonic, ascending and descending phases of the ramp exertions. For AEMG, a series of 3 × 4 mixed ANOVAs were used to test for statistical differences between the four compartments of ED and FDS at each level of force (3 exertion modes and 4 muscular compartments). Each ED (and FDS, separately) compartment was compared against the other 3 compartments to determine the effect of the voluntary exertion of the task finger on the other compartments (PASW Statistics 18, SPSS Inc., IL, USA). Significant effects were further investigated using Tukey's HSD post-hoc analysis. The Pearson product-moment correlation coefficient was also calculated for each of the 3 exertion modes to determine the relationship between the AEMG of all the flexor and extensor compartments and the exertion force by the task finger.

3.4. Results

3.4.1. Enslaving Effect

A summary of the maximal exertion forces in all 3 exertion conditions for all fingers is presented in Table 3.2. Considerable enslaving was observed in this study. The general trend was that the enslaving effect (EE) increased with increasing exertion force of the task finger. The EE was higher in adjacent versus non-adjacent fingers. The EE was also generally higher in extension than flexion exertions. A pictorial summary of enslaving forces during EXT, FLXp and FLXd exertions of all fingers similar to that of Zatsiorsky at al. (2000) is found in Figure 3.3. Similar effects were noted for EXT, FLXp and FLXd exertions for all fingers (with the exception of middle finger EXT). For each, there was a statistically significant finger × exertion mode interaction of EE at 25 and 50% MVC (EXT, all $F_{4,44} > 4.86$, all $p < 0.002$; FLXp, all $F_{4,44} > 3.97$, all $p < 0.008$; FLXd, all $F_{4,44} > 12.39$, all $p < 0.0001$). At 75% MVC, only a main effect of finger on EE was found during index, ring and little EXT exertions (all $F_{2,22} > 34.19$, all $p < 0.0001$) and index, middle and ring FLXp and FLXd exertions (FLXp, all $F_{2,22} > 7.64$, all $p < 0.003$; FLXd, all $F_{2,22} > 10.06$, all $p < 0.001$).

****

Figure 3.3

****

****

Table 3.2

****

During EXT trials, the index finger was the most independent (lowest EE) while the little finger had the highest EE (Figure 3.3). At 25 and 50% MVC, a finger × exertion mode interaction was found to be due to EE being greater in adjacent fingers and descending exertions (Figure 3.4a). At 75% MVC, a main effect of finger was found for exertions of the index, ring and little fingers (all $F_{2,22} > 34.19$, all $p < 0.0001$) but no significant differences were found between exertion modes (Figure 3.4b). Post-hoc analysis of the 75% MVC exertions revealed that the adjacent finger(s) had significantly higher EE than non-adjacent fingers in all exertion modes (Figure 3.4b) . Enslaving forces of the adjacent fingers ranged from 2.5 ± 0.9% MVC (index finger during 25% MVC ascending exertion of middle finger) to 65.5 ± 4.9% MVC (ring finger during descending exertion of little finger at 75%). During ring finger exertions, EE for the two adjacent non-task fingers were not significantly different. Occasionaly, non-task fingers produced forces in the direction opposite to the exertion of the task finger.

****

Figure 3.4

****

In the FLXp and FLXd trials, significant finger × exertion mode interactions at 25 and 50% exertions of index and ring fingers were due to higher EE in adjacent fingers only during the descending exertions (Figure 3.4c). Unlike the EXT exertions, the EE was not significantly different between the non-task fingers during the ascending and isotonic exertions (Figure 3.4a vs. 3.4c). The highest EE in the FLXp condition was 41.7 ± 6.5% MVC for the ring finger at 75% force on the descending phase of the little finger. Isotonic FLXp and FLXd exertions of the index finger resulted in minimal enslaving force on all fingers (Figure 3.3). During FLXd trials, EEs were lowest during index finger exertions (all less than 8.7 ± 1.6% MVC which was found in the descending exertion), followed by middle and ring fingers, and highest during little finger exertions (up to 36.5 ± 5.4% MVC in the descending exertion).

3.4.2. Average EMG

AEMG of all compartments increased with exertion force. There was a significant positive linear relationship between all (agonist and antagonist) AEMG and the 4 exertion levels of the task finger (all $r \geq 0.96$, $p < 0.05$; Figure 3.5). ED AEMG (all compartments) was generally higher during flexion exertions than the FDS compartments during EXT (Figure 3.5).

****

Figure 3.5

****

In EXT exertions of the index, middle and little fingers, a significant compartment × exertion mode interaction was found at 25 and 50% MVC (all $F_{6,66} > 4.56$, all $p < 0.001$). The task compartment had higher AEMG during the isotonic and ascending exertions than the descending exertion while the opposite trend was observed in non-task compartments with the descending exertion resulting in higher AEMG (Figure 3.6a). As expected, ED3 had the highest activity among the compartments during middle finger exertions while ED4 and ED5 had similar activities (Figure 3.6a). ED4 and ED5 had similar activity during exertions of the little finger and both were significantly than ED2 and ED3 at all force levels in all exertion modes. There was a main effect of ED compartment during the exertions of the index, middle and little fingers at the 75% MVC force level (both $F_{3,33} > 9.25$, both $p < 0.0001$). The antagonist FDS compartments had minimal activity during extension exertions (under 8% MVE) with no significant differences between compartments or exertion modes.

****

Figure 3.6

****

For both FLXp and FLXd exertions, FDS compartment had a main effect on AEMG during middle and ring finger exertions at 50 and 75% MVC (all $F_{3,33} > 3.34$, all $p < 0.03$). For middle finger exertions, both FDS3 (task compartment) and FDS2 (adjacent) had significantly higher AEMG than FDS4 and FDS5 (Figure 3.6b). Similarly, during ring finger exertions, FDS4 (task) and FDS5 (adjacent) had significantly greater activity than FDS2 and FDS3. Exertion mode significantly altered AEMG during FLXp exertions of the little finger and FLXd exertions of the index finger at the 25 and 50% MVC (all $F_{2,22} > 9.62$, all $p < 0.002$) with the isotonic and ascending modes having significantly lower activity than the descending mode. During both FLXp and FLXd exertions, there was a significant main effect of exertion mode on AEMG of the antagonist compartments (ED) during the 25% MVC exertions of all fingers in FLXp (all $F_{2,22} > 6.67$, all $p < 0.005$) and the index, middle and little fingers in FLXd (all $F_{2,22} > 4.23$, all $p < 0.03$). In all of these trials, the isotonic and ascending ramp exertions had lower activity than the descending portion of the exertion (Figure 3.6c).

3.5. Discussion

The present study adds to the understanding of finger control and muscular activation under varying exertion modes. We found that the enslaving effect was dependent on finger and exertion mode for most exertions at 25 and 50% MVC. At 75% MVC, EE was only finger dependent and independent of the exertion mode. ED and FDS compartment AEMG differed by exertion type depending on force level. In 25 and 50% EXT contractions, ED compartment activity was dependent on both the proximity to the task compartment and the exertion mode. The activity of ED compartments at 75% EXT and FDS compartments at 50 and 75% MVC flexion exertions were only dependent on the proximity of the compartment and not exertion mode. Considering both EE and AEMG, our results collectively suggest that up to 50% MVC, descending exertion imposes the greatest challenge to the neuromuscular control of the fingers. Finally, we found exertion mode had a differential effect on the extensor and flexor muscle compartments. In extension, the task and adjacent compartments of ED were less active during the descending exertions than isotonic or ascending modes while the opposite was observed for the non-adjacent compartments. In flexion, the activities of all compartments (task, adjacent and non-adjacent) were higher during the descending exertion versus the isotonic and ascending exertions (Figure 3.6a vs. 3.6b).

Another major finding of this study was that the fingers were generally less independent when exerting force in extension than flexion as previously reported (van Duinen et al., 2009). Finger independence has been qualitatively assessed based on finger movements in flexion and extension and but not in terms of the ability of fingers to exclusively exert static forces (Robinson and Fuglevand, 1999). In the present study, the index finger produced lower involuntary forces than all the other digits in both flexion and extension which is consistent with previous studies finding index finger to be the most independent (Robinson and Fuglevand, 1999; McIsaac and Fuglevand, 2007; Slobounov et al., 2002a). Slobounov et al. (2002a) and Robinson and Fuglevand (1999) found the ring finger to be the least independent finger in both extension and flexion. Even though we found little finger exertions produced the highest enslaving forces on the adjacent ring finger, when considering the overall enslaving effects, we also found the ring finger to be the least independent since it produced the highest combined enslaving forces on the two adjacent middle and little fingers. Furthermore, our AEMG results also indicated that all the ED compartments had similar activities during extension exertions of the ring finger in all exertion modes at all force levels. Previously, Keen and Fuglevand (2004) have also found synchronous firing of motor units to be highest between ED3 – ED4 and ED4 – ED5 compartments. Lastly, Slobounov et al. (2002a) found similar but slightly higher EE during fingertip flexion exertions at all 3 force levels as our FLXd exertions. The slight differences are likely due to the orientation of the hand (vertical vs. horizontal in Slobounov et al. (2002a)).

Similar to the findings of previous studies, we found higher enslaving forces in adjacent versus non-adjacent fingers (Zatsiorsky et al., 1998; Slobounov et al., 2002a). With a few exceptions, we found that adjacent FDS compartments had higher activity than non-adjacent compartments during flexion exertions which may indicate involuntary activitation due to a "spill-over" effect. The 'spill-over' hypothesis suggests that cortical motor commands to one extrinsic finger flexor compartment gradually spills over to more remote flexor compartments (Kilbreath and Gandevia, 1994). Similar findings from single motor unit activities in non-task ED and FDS compartments during single digit exertions have been reported previously (Butler et al., 2005; van Duinen et al., 2009).

Simultaneous recording of all four ED and FDS compartments allowed us to investigate the role of the antagonist compartments in finger control during static exertions. We found that the ED compartments had higher activity during flexion exertions than the FDS compartments during extension exertions (Figure 3.5). Higher activity of antagonist ED compartments during flexion exertions likely counter-balanced involuntary activation of the FDS and FDP compartments not directly involved in force production resulting in lower EE in flexion than extension. FDP compartment activity has previously been reported in the non-task fingers during weak extension exertions (Reilly and Schieber, 2003) and it has been suggested that simultaneous activation of agonists and antagonist during static fingertip force production is unavoidable in many instances (Valero-Cuevas, 2005). Functionally, the antagonists have been hypothesized to contribute to joint stiffness (Maier and Hepp-Reymond, 1995b), stability (Li et al., 2000) and a reduction of the EE on the non-task fingers (Reilly and Schieber, 2003).

The nervous system has the ability to modulate fingertip forces by scaling relative activities of all the intrinsic and extrinsic muscles of the finger (Valero-Cuevas, 2005). During flexion exertions, we found considerable activity, not only in the compartment directly antagonist to the task compartment, but also in all antagonist compartments, which were highly correlated with exertion level. It has been hypothesized that the activity of the antagonist ED muscle is exclusively modulated only at higher force levels during a precision grip in order to balance the applied force and maintain joint equilibrium (Maier and Hepp-Reymond, 1995a). Scaling of ED activity during precision grip at high force levels has also been shown in monkeys (Rufener and Hepp-Reymond, 1988). Exclusive modulation of each antagonist compartment during static single finger exertions seems computationally complex. A less complicated explanation would be that mechanical (anatomical) or peripheral neural driven restrictions might result in coupling between the antagonist compartment serving the task finger and all the other antagonist compartments.

In the present study, we found significant positive linear correlations between AEMG and exertion level not only for the task finger, but all agonist and antagonist compartments ($r \geq 0.96$). High correlation between AEMG and the exertion force has been previously reported by Danion et al. (2002) during flexion exertions of all four fingers ($R = 0.99$). However, that study used only one site to record activity of the extrinsic finger flexors while we used four sites. Valero-Cuevas (2000) also reported a high correlation between the activity of the extrinsic finger flexors (FDS and FDP) and extensors (EDC and EI) during static flexion and extension exertions of the index finger. A high level of consistency in the descending motor command might explain the correlation between exertion level and AEMG of both the agonist and antagonist muscular compartments serving the task finger (Maier and Hepp-Reymond, 1995a; Valero-Cuevas, 2000).

Most of our subjects reported difficulty in controlling the force during the descending phase of the ramp exertion as seen in higher enslaving forces during the descending exertions than the isotonic and ascending exertions in both flexion and extension (Figures 3.4). Based on our results, the difficulty in linearly decreasing finger flexion force at 25% MVC may be due to higher activities in the non-task compartments of FDS. Interestingly, we found significantly higher antagonist activities (ED) during the descending flexion exertions as well (Figure 3.6c). However, even the increased activity of the ED compartments is likely insufficient to counterbalance the activity in the non-task FDS compartments resulting in considerably greater enslaving forces during the descending exertions.

There are a few limitations to the present study. The use of surface electrodes introduces issues of selectivity and the possibility of crosstalk. To minimize the potential of these confounding effects, we followed the guidelines of Leijnse et al. (2008a,b) for ED and Burgar et al. (1997) for FDS compartment electrode placements with detailed functional and anatomical testing to confirm electrode placement. While our application differed, Mogk and Keir (2003) concluded that minimal cross-talk should be expected between well placed electrodes on the flexor and extensor sides of the forearm. Another limitation of the study was that our subjects had some difficulty during the ramp-down phase of the triangular exertions resulting in a rapid drop in force at the start of the descent. We attempted to minimize this effect with the addition of a 0.5-second plateau after the ascending phase which pilot wotk suggested would facilitate a more accurate start to the ramp-down phase.

3.6. Conclusion

Both exertion mode and proximity to the task finger or muscular compartment were found to affect involuntary force production and muscle activity during finger flexion and extension exertions. At exertion levels equal to, or lower than, 50% the gradual decrease in force during the descending exertion proved most challenging in terms of finger independence and control as both enslaving effects and the activation of the non-task ED and FDS compartment were higher than the isotonic and ascending exertions. The type of exertion did not seem to affect finger independence and control at higher force levels (75% MVC). The proximity of the non-task fingers, and to a lesser extent, non-task muscular compartments influenced the enslaving forces and muscular activation at all force levels. The extrinsic finger extensors were more active during flexion exertions than vice versa. While activation of the uninvolved agonist compartments was inevitable, the substantial activation of the (antagonist) extensor compartments seemed to at least partially counter balance the involuntary activation of the non-task FDS compartments to potentially reduce the enslaving magnitude on the non-task fingers during flexion exertions. In general, fingers were more independent in flexion compared to extension which could be partially explained by the higher activity of the antagonist extensor during flexion exertions. Future studies should further evaluate descending force control and involuntary activation and force production in functional tasks such as typing.

Acknowledgements

This study was funded by a Discovery Grant from the Natural Sciences and Engineering Reasearch Council of Canada (#217382).

3.7. References

Burgar CG, Valero-Cuevas FJ, and Hentz VR. Fine-wire electromyographic recording during force generation. Application to index finger kinesiologic studies. Am J Phys Med Rehabil 1997;76(6):494-501.

Butler TJ, Kilbreath SL, Gorman RB, and Gandevia SC. Selective recruitment of single motor units in human flexor digitorum superficialis muscle during flexion of individual fingers. J Physiol 2005;567(Pt 1):301-9.

Danion F, Li S, Zatsiorsky VM, and Latash ML. Relations between surface EMG of extrinsic flexors and individual finger forces support the notion of muscle compartments. Eur J Appl Physiol 2002;88(1-2):185-8.

Kaplan, EB. Anatomy, injuries and treatment of the extensor apparatus of the hand. Clinic Orthop 1959;13:24-41.

Keen DA, Fuglevand AJ. Role of intertendinous connections in distribution of force in the human extensor digitorum muscle. Muscle Nerve 2003;28(5):614-22.

Keen DA and Fuglevand AJ. Common input to motor neurons innervating the same and different compartments of the human extensor digitorum muscle. J Neurophysiol 2004;91(1):57-62.

Kilbreath SL, Gandevia SC. Limited independent flexion of the thumb and fingers in human subjects. J Physiol 1994;479 (Pt 3):487-97.

Leijnse JN, Campbell-Kyureghyan NH, Spektor D, and Quesada PM. Assessment of individual finger muscle activity in the extensor digitorum communis by surface EMG. J Neurophysiol 2008;100(6):3225-35.

Leijnse JN, Carter S, Gupta A, and McCabe S. Anatomic basis for individuated surface EMG and homogeneous electrostimulation with neuroprostheses of the extensor digitorum communis. J Neurophysiol 2008;100(1):64-75.

Li ZM, Zatsiorsky VM, and Latash ML. Contribution of the extrinsic and intrinsic hand muscles to the moments in finger joints. Clin Biomech (Bristol , Avon) 2000;15(3):203-11.

Maier MA, Hepp-Reymond MC. EMG activation patterns during force production in precision grip. I. Contribution of 15 finger muscles to isometric force. Exp Brain Res 1995a;103(1):108-22.

Maier MA, Hepp-Reymond MC. EMG activation patterns during force production in precision grip. II. Muscular synergies in the spatial and temporal domain. Exp Brain Res 1995b;103(1):123-36.

McIsaac TL, Fuglevand AJ. Motor-unit synchrony within and across compartments of the human flexor digitorum superficialis. J Neurophysiol 2007;97(1):550-6.

Mogk JP, Keir PJ. Crosstalk in surface electromyography of the proximal forearm during gripping tasks. J Electromyogr Kinesiol 2003;13(1):63-71.

Perotto AO, Delagi EF, Iazzetti J, Morrison D. Anatomical guide for the electromyographer: The limbs and trunk. 4th ed. Illinois: Charles C Thomas, 2004.

Reilly KT, Hammond GR. Independence of force production by digits of the human hand. Neurosci Lett 2000;290(1):53-6.

Reilly KT, Schieber MH. Incomplete functional subdivision of the human multitendoned finger muscle flexor digitorum profundus: an electromyographic study. J Neurophysiol 2003;90(4):2560-70.

Reilly KT, Nordstrom MA, and Schieber MH. Short-term synchronization between motor units in different functional subdivisions of the human flexor digitorum profundus muscle. J Neurophysiol 2004;92(2):734-42.

Robinson TL, Fuglevand AJ. Independence of finger movements in normal subjects and in concert level pianists. Soc Neurosci Abstr 1999;25:1149.

Rufener EA, Hepp-Reymond MC. Muscle coactivation patterns in the precision grip. Adv Biosci 1988;70:169-72.

Schieber MH, Hibbard LS. How somatotopic is the motor cortex hand area? Science 1993;261(5120):489-92.

Schieber MH, Santello M. Hand function: peripheral and central constraints on performance. J Appl Physiol 2004;96(6):2293-300.

Schuenke M, Schulte E, Schumacher U. Thieme atlas of anatomy: general anatomy and musculoskeletal system. 3rd ed. New Jersey: Icon Learning System, 2003.

Shim JK, Olafsdottir H, Zatsiorsky VM, and Latash ML. The emergence and disappearance of multi-digit synergies during force-production tasks. Exp Brain Res 2005;164(2):260-70.

Slobounov S, Johnston J, Chiang H, and Ray W. The role of sub-maximal force production in the enslaving phenomenon. Brain Res 2002a;954(2):212-9.

Slobounov S, Chiang H, Johnston J, and Ray W. Modulated cortical control of individual fingers in experienced musicians: an EEG study. Electroencephalographic study. Clin Neurophysiol 2002b;113(12):2013-24.

Valero-Cuevas FJ. Predictive modulation of muscle coordination pattern magnitude scales fingertip force magnitude over the voluntary range. J Neurophysiol 2000;83(3):1469-79.

Valero-Cuevas FJ. An integrative approach to the biomechanical function and neuromuscular control of the fingers. J Biomech 2005;38(4):673-84.

Valero-Cuevas FJ. Why the hand? Adv Exp Med Biol 2009;629:553-7.

van DH, Yu WS, and Gandevia SC. Limited ability to extend the digits of the human hand independently with extensor digitorum. J Physiol 2009;587(Pt 20):4799-810.

von Schroeder HP, Botte MJ, and Gellman H. Anatomy of the juncturae tendinum of the hand. J Hand Surg Am 1990;15(4):595-602.

Zatsiorsky VM, Li ZM, and Latash ML. Coordinated force production in multi-finger tasks: finger interaction and neural network modeling. Biol Cybern 1998;79(2):139-50.

Zatsiorsky VM, Li ZM, and Latash ML. Enslaving effects in multi-finger force production. Exp Brain Res 2000;131(2):187-95.

3.8. Manuscript Tables and Figures

3.8.1. Tables

Table 3.1. Electrode locations of ED and FDS compartments

Compartment	Electrode Location
ED2	Mid-forearm on the medial border
ED3	Distal to the humeroradial joint at the midline of ED
ED4	Mid-forearm parallel to ED2 at ulnar border
ED5/EDM	Mid-forearm (or more distal according to palpation), medial to ED4 electrodes
FDS2	Distal third of forearm on the lateral border of ulna
FDS3	Proximal half of forearm on the medial border of radius
FDS4	Middle third of forearm on the medial border of radius
FDS5	Distal half of forearm on the medial border of ulna

Table 3.2. Maximal exertion forces (N) of all fingers during EXT, FLXp and FLXd exertions (Mean ± SD, n =12)

	EXT	FLXp	FLXd
Index	35.7 ± 9.7	56.6 ± 8.7	50.7 ± 11.3
Middle	30.5 ± 7.4	50.6 ± 10.6	49.4 ± 13.5
Ring	17.1 ± 5.8	32.5 ± 6.5	32.8 ± 8.5
Little	19.3 ± 4.1	32.8 ± 6.5	27.4 ± 6.5

Supplementary tables to be submitted with the manuscript.

Table 3.3. Average EE (% MVC ± SE, n=12) of index (I), middle (M), ring (R), and little (L) fingers during (a) isotonic, (b) ascending and (c) descending exertions at 25, 50 and 75 % MVC force levels. The task and non-task fingers are listed in the second column and row of the table respectively. The exertion forces of the task fingers are represented as a reference (bold, italic numbers). Negative denotes forces being exerted in direction opposite to task finger. Adapted from Zatsiorsky et al. (1998).

a)

	Task	EXT				FLXp				FLXd			
		I	M	R	L	I	M	R	L	I	M	R	L
25 (% MVC)	I	***25***	6.0 ± 1.2	3.5 ± 1.1	2.5 ± 1.3	***25***	0.8 ± 0.5	0.8 ± 0.3	0.7 ± 0.5	***25***	0.5 ± 0.4	0.8 ± 0.2	1.0 ± 0.5
	M	4 ± 1	***25***	6.5 ± 1.4	2.5 ± 0.9	1.5 ± 0.6	***25***	3.1 ± 0.3	-0.1 ± 0.6	1.3 ± 0.6	***25***	2.9 ± 0.5	0.1 ± 0.5
	R	1.2 ± 0.7	11.6 ± 1.9	***25***	11.2 ± 1.2	0.1 ± 0.3	3.1 ± 0.8	***25***	1.1 ± 0.8	-0.2 ± 0.3	3.3 ± 0.7	***25***	0.4 ± 0.9
	L	1.0 ± 0.4	6.9 ± 1.1	11.2 ± 1.7	***25***	0.3 ± 0.2	0 ± 0.7	4.3 ± 0.8	***25***	0.3 ± 0.3	0.3 ± 0.6	5.1 ± 1.0	***25***
50 (% MVC)	I	***50***	13.5 ± 3	3.7 ± 1.4	1.3 ± 2.1	***50***	2.3 ± 0.7	0.7 ± 0.4	1.0 ± 0.5	***50***	1.8 ± 1.0	0.8 ± 0.4	1.5 ± 0.6
	M	7.1 ± 2.6	***50***	15.6 ± 3.2	2.3 ± 1.7	3.8 ± 1	***50***	6.5 ± 1.2	-1.5 ± 0.9	2.2 ± 1.1	***50***	7.4 ± 1.5	-0.9 ± 0.8
	R	-0.4 ± 0.9	19.6 ± 2.9	***50***	20.5 ± 2.8	0.2 ± 0.6	6.8 ± 2	***50***	2.8 ± 1.6	-1.2 ± 0.9	6.8 ± 1.8	***50***	4.3 ± 2.2
	L	-1.1 ± 0.7	9.1 ± 2.5	30.0 ± 4.8	***50***	0.6 ± 0.7	0 ± 1.1	10.9 ± 2.3	***50***	-0.4 ± 0.7	-0.2 ± 1.2	9.9 ± 1.9	***50***
75 (% MVC)	I	***75***	35.1 ± 5.2	9.2 ± 3.3	0.4 ± 2.5	***75***	6.3 ± 1	1.1 ± 0.8	1 ± 0.9	***75***	7.2 ± 1.7	0.2 ± 0.8	1.9 ± 0.9
	M	18.4 ± 4.4	***75***	42.0 ± 5.6	13.5 ± 4.1	7.2 ± 2.9	***75***	14.3 ± 3.1	-3.6 ± 1.7	3.5 ± 1.9	***75***	17.8 ± 3.7	-2.5 ± 1.7
	R	-0.2 ± 1.6	40.1 ± 4.7	***75***	45.6 ± 3.3	-0.1 ± 0.8	16.1 ± 3.1	***75***	7.0 ± 2.6	-2.6 ± 1.7	16.4 ± 3.2	***75***	12.5 ± 3.1
	L	-2.9 ± 1.7	17.0 ± 5.9	60.5 ± 4.8	***75***	0.4 ± 0.7	1.4 ± 1.5	31.9 ± 5.1	***75***	-1.2 ± 2.1	1.4 ± 2.1	28.5 ± 4.9	***75***

b)

	Task	EXT				FLXp				FLXd			
		I	M	R	L	I	M	R	L	I	M	R	L
25 (% MVC)	I	***25***	4.6 ± 0.9	1.1 ± 0.6	0.2 ± 0.5	***25***	0.8 ± 0.5	0.4 ± 0.3	0.4 ± 0.3	***25***	0.9 ± 0.3	0.6 ± 0.2	0.3 ± 0.3
	M	2.5 ± 0.9	***25***	4.6 ± 1.2	1.1 ± 0.6	1.1 ± 0.8	***25***	3.0 ± 0.7	-0.4 ± 0.5	0.2 ± 0.4	***25***	2.6 ± 0.7	-0.5 ± 0.4
	R	0.3 ± 0.6	10.4 ± 1.8	***25***	10.5 ± 1.6	-0.2 ± 0.5	3.0 ± 1.0	***25***	0.5 ± 1.1	-0.8 ± 0.4	2.5 ± 1.0	***25***	0.6 ± 0.9
	L	0.1 ± 0.5	5.1 ± 1.0	8.9 ± 1.8	***25***	-0.3 ± 0.4	0.1 ± 0.4	3.4 ± 0.7	***25***	0.2 ± 0.3	-0.1 ± 0.9	3.6 ± 0.9	***25***
50 (% MVC)	I	***50***	10.8 ± 2.2	3.5 ± 1.0	1.4 ± 1.0	***50***	2.9 ± 1.4	0.7 ± 0.5	0.3 ± 0.5	***50***	1.9 ± 0.7	0.9 ± 0.3	0.8 ± 0.2
	M	6.6 ± 1.7	***50***	11.5 ± 2.5	1.5 ± 1.2	3.0 ± 1.4	***50***	6.6 ± 1.4	-2.3 ± 0.8	0.7 ± 1.1	***50***	7.0 ± 1.8	-1.9 ± 1.0
	R	0 ± 0.7	19.1 ± 2.5	***50***	20.6 ± 2.9	-0.4 ± 0.6	7.6 ± 1.7	***50***	2.8 ± 2.3	-2.1 ± 1.0	7.6 ± 1.9	***50***	2.8 ± 2.1
	L	-0.9 ± 1.1	10.9 ± 3.2	28.6 ± 4.1	***50***	0.1 ± 0.5	0.4 ± 0.7	12.5 ± 2.4	***50***	-0.4 ± 0.9	-0.8 ± 1.6	12.2 ± 2.1	***50***
75 (% MVC)	I	***75***	28.1 ± 4.4	5.7 ± 2.2	-3.2 ± 1.7	***75***	7.2 ± 3.2	1.0 ± 0.7	0.1 ± 0.7	***75***	4.0 ± 1.4	-0.5 ± 0.6	1.0 ± 0.4
	M	17.4 ± 3.0	***75***	32.4 ± 5.5	5.8 ± 3.0	7.4 ± 3.3	***75***	14.4 ± 3.8	-4.5 ± 1.9	4.8 ± 2.3	***75***	17.7 ± 4.0	-4.6 ± 3.4
	R	-1.1 ± 1.1	41.2 ± 4.8	***75***	42.1 ± 4.5	-1.8 ± 1.0	21.2 ± 3.6	***75***	10.4 ± 5.0	-3.9 ± 1.8	17.2 ± 2.4	***75***	10.6 ± 3.4
	L	-4.9 ± 1.6	15.6 ± 6.4	61.6 ± 5.0	***75***	-0.5 ± 1.1	2.1 ± 1.7	30.5 ± 5.0	***75***	-1.2 ± 1.4	-1.9 ± 2.3	28.8 ± 4.5	***75***

c)

	Task	EXT				FLXp				FLXd			
		I	M	R	L	I	M	R	L	I	M	R	L
25 (% MVC)	I	**25**	18.1 ± 2.3	5.1 ± 1.5	-0.3 ± 1.1	**25**	6.7 ± 1.6	0.7 ± 0.5	0.7 ± 0.6	**25**	5.4 ± 0.9	0.4 ± 0.4	0.6 ± 0.4
	M	11.3 ± 1.3	**25**	13.4 ± 2.3	5.1 ± 1.9	4.4 ± 1.0	**25**	6.9 ± 1.4	-0.2 ± 1.6	4.6 ± 1.1	**25**	9.7 ± 2	0.2 ± 1.2
	R	1.4 ± 0.6	20.8 ± 2.7	**25**	17.1 ± 2.4	-0.1 ± 0.7	12.8 ± 2.1	**25**	6.3 ± 2.6	-0.3 ± 0.6	11.6 ± 1.0	**25**	5.8 ± 1.4
	L	-1.3 ± 0.9	12.7 ± 4.6	24.4 ± 3.4	**25**	-0.1 ± 0.6	4.7 ± 1.4	15.7 ± 2.2	**25**	-0.4 ± 0.4	1.5 ± 0.9	14.6 ± 2.2	**25**
50 (% MVC)	I	**50**	26.0 ± 3.5	7.4 ± 1.9	-1.1 ± 1.9	**50**	11 ± 2.7	1.7 ± 0.9	0.9 ± 0.6	**50**	8.7 ± 1.6	0.8 ± 0.6	1.3 ± 0.7
	M	19.4 ± 2.6	**50**	25.1 ± 3.9	8.6 ± 3.1	9.6 ± 2.5	**50**	14.4 ± 2.6	-0.1 ± 2.7	8.9 ± 1.9	**50**	18.3 ± 3.1	-0.1 ± 1.9
	R	1.7 ± 1.2	35.5 ± 3.5	**50**	31.9 ± 2.7	0.2 ± 1.1	23.1 ± 3	**50**	11.7 ± 4.1	-0.4 ± 0.9	21.1 ± 1.7	**50**	12.2 ± 2.5
	L	-2.1 ± 1.2	18.4 ± 5.4	43.8 ± 4.1	**50**	-0.3 ± 1.0	8.0 ± 1.9	32.5 ± 3.6	**50**	-0.7 ± 1.1	3.6 ± 1.8	28.7 ± 3.5	**50**
75 (% MVC)	I	**75**	33.9 ± 4.7	8.3 ± 2.7	-2.4 ± 1.9	**75**	11.3 ± 4.3	1.4 ± 1.2	0.6 ± 0.7	**75**	8.1 ± 2.1	-0.1 ± 0.7	1.4 ± 0.8
	M	24.9 ± 4.1	**75**	38.9 ± 5.9	11.5 ± 4.3	8.8 ± 3.8	**75**	17.4 ± 4.8	-2.6 ± 3.3	7.3 ± 2.6	**75**	22.1 ± 4.4	-4.4 ± 4.0
	R	-0.5 ± 1.5	46.2 ± 4.3	**75**	45.4 ± 3.8	-1. 4± 1.3	28.0 ± 3.5	**75**	15.6 ± 4.9	-3.9 ± 1.7	20 ± 2.3	**75**	13.7 ± 3.4
	L	-5.5 ± 1.9	18.7 ± 7.1	65.5 ± 4.9	**75**	-0.9 ± 1.4	5.2 ± 2.2	41.7 ± 6.5	**75**	-1.9 ± 1.8	-0.6 ± 2.3	36.5 ± 5.4	**75**

3.8.2. Figure Captions

Figure 3.1. Experimental setup. Fingers were placed in adjustable metal rings attached to force transducers. Rings were moved along the length of the finger on the plate. Wrist was supported and splinted.

Figure 3.2. Schematic illustration of (a) isotonic and (b) ramp exertions. In isotonic exertions, for a given level of force, each finger exerted for 5 seconds with 5 seconds between exertions of different fingers. There was 30 seconds between consecutive trials. During ramp exertions, each of the ascending and descending phases were 4.5 seconds each with a 0.5 second plateau at 85% MVC.

Figure 3.3. Graphic mapping of enslaving effects between index (I), middle (M), ring (R), and little (L) fingers during isotonic EXT, FLXp and FLXd exertions at 25, 50 and 75% MVC. Numbers represent enslaving effect (in %). Arrow direction from "master" finger to the "slave" finger. The line thickness is proportional to the enslaving force. Negative denotes forces being exerted in direction opposite to task finger. Adapted from Zatsiorsky et al. (2000).

Figure 3.4. Enslaving effect (% MVC ± SE) during isotonic (ISO), ascending (ASC) and descending (DES) phases of the ramp index finger exertions at (a) 50 and (b) 75% MVC EXT; and (c) 50% MVC FLXd. There were significant interactions between finger and exertion modes in (a) and (c). There was a main effect of finger in (b) and no significant differences between the exertion modes. Different letters denote

significant differences ($p < 0.05$) between EE within each exertion mode. Negative denotes forces being exerted in direction opposite to task finger.

Figure 3.5. AEMG (% MVE) of all ED and FDS compartments for all 4 exertion levels of index finger in (a) EXT, (b) FLXp and (c) FLXd during isotonic exertions.

Figure 3.6. AEMG (% MVE ± SE) of (a) ED compartments in EXT and (b) FDS compartments in FLXd during the 3 exertion modes of the middle finger at 50% MVC. There was a significant finger × exertion modes interaction in (a) and a significant main effect of compartment in (b). Different letters denote significant differences ($p < 0.05$) between AEMGs within each exertion mode. (c) The AEMG of the antagonist ED compartments during 25% MVC FLXp exertions of all fingers. There was a significant main effect of exertion mode. An average of all 4 ED compartments has been presented. Different letters denote significant differences ($p < 0.05$) between exertion modes.

3.8.3. Figures

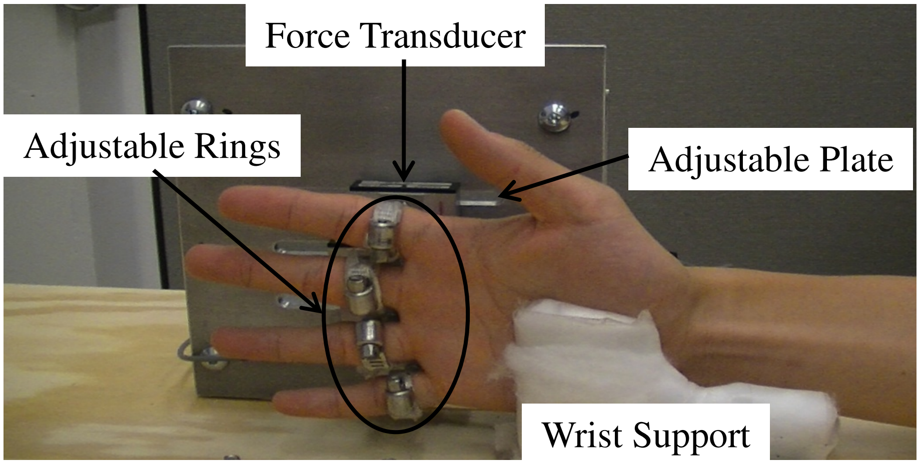


Figure 3.1. Experimental set-up.

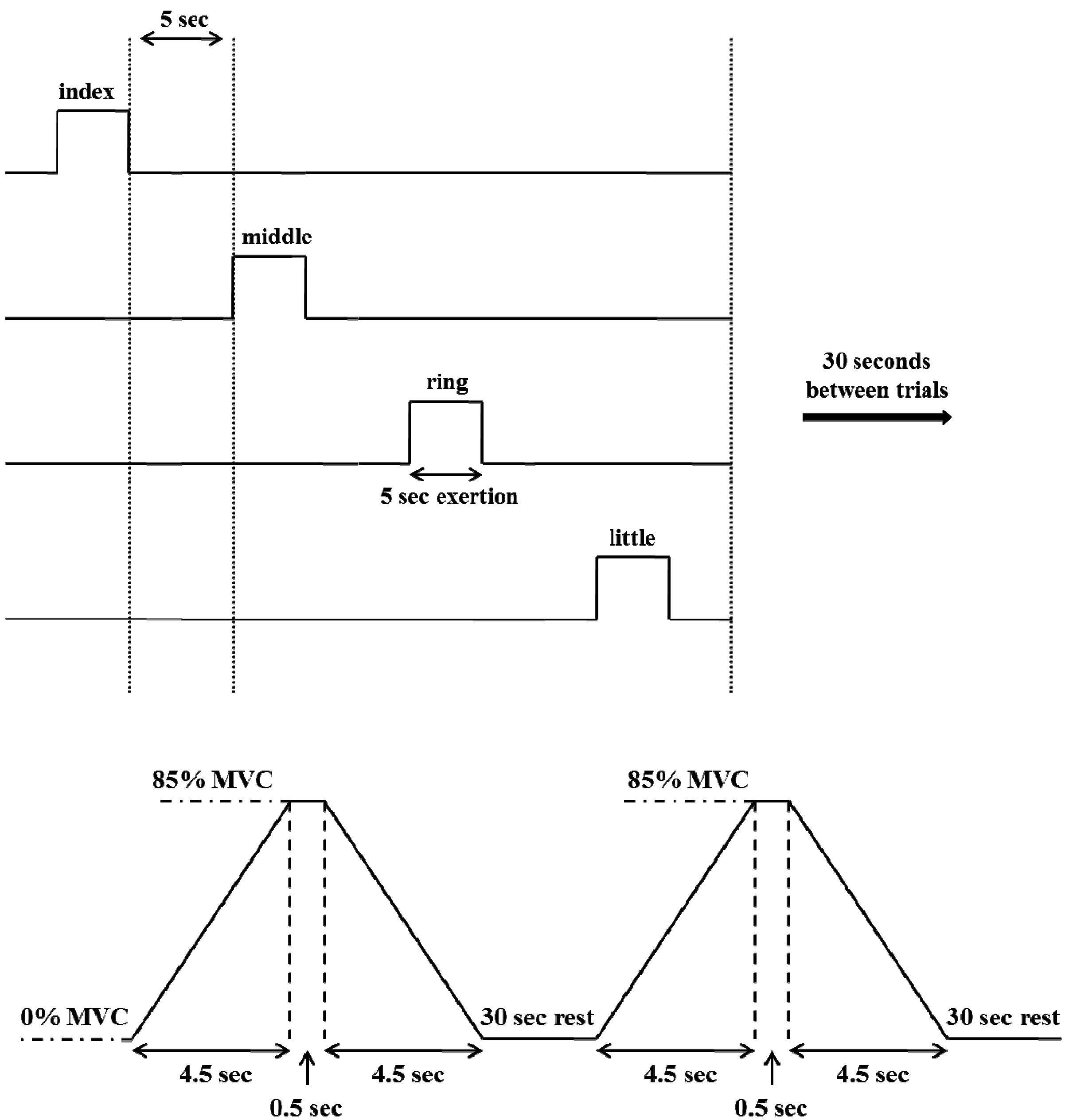


Figure 3.2. Schematic representation of study protocol, (a) isotonic and (b) ramp exertions.

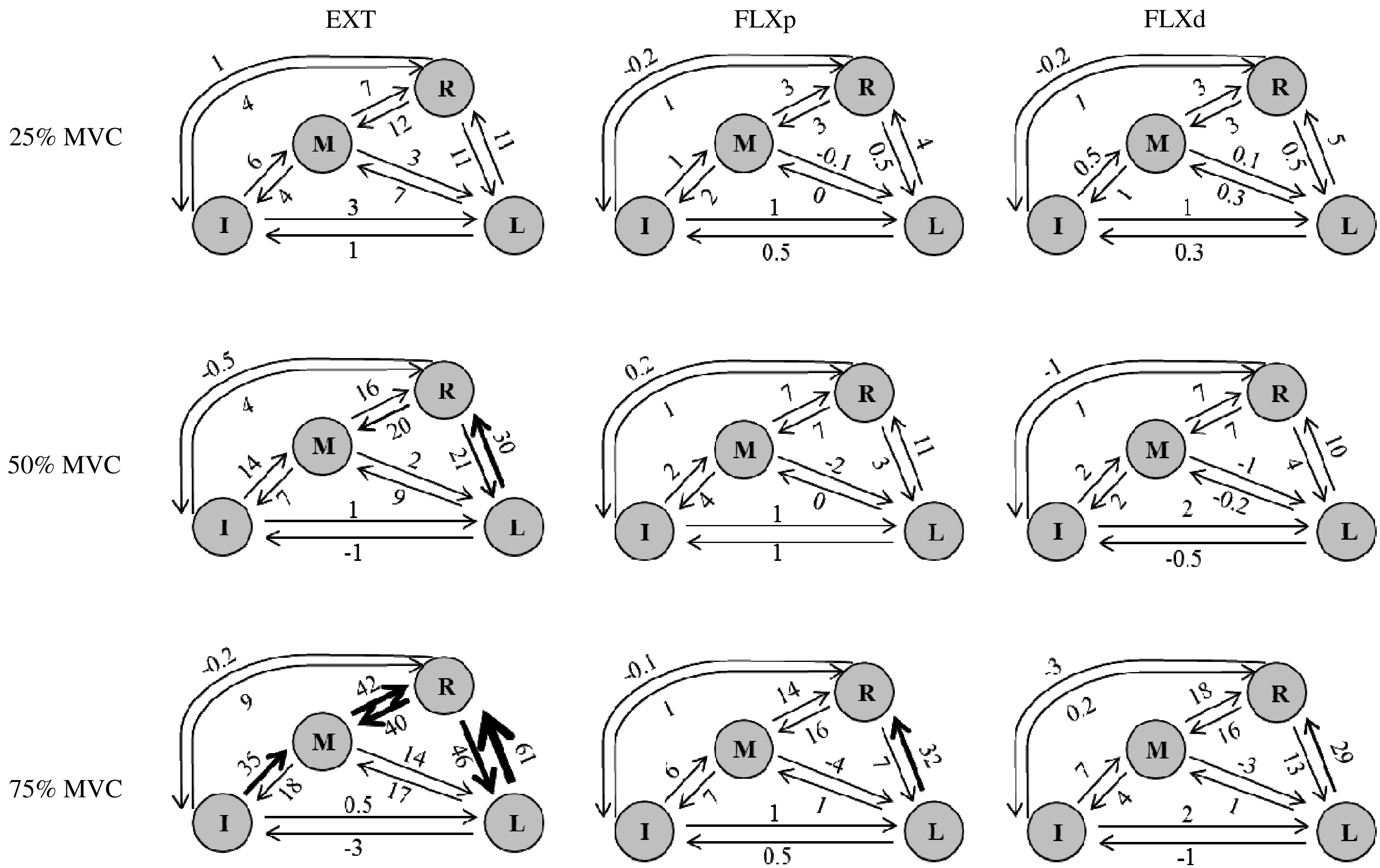
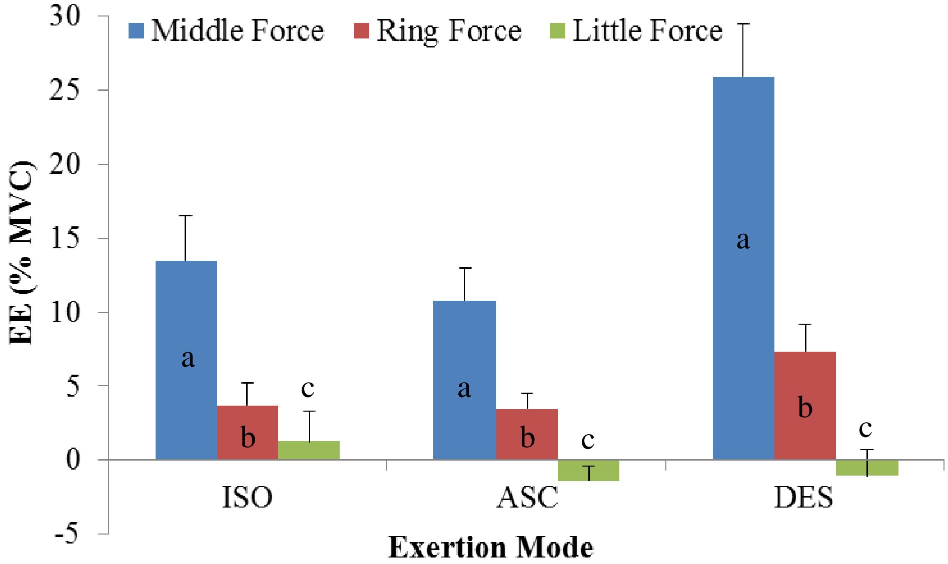
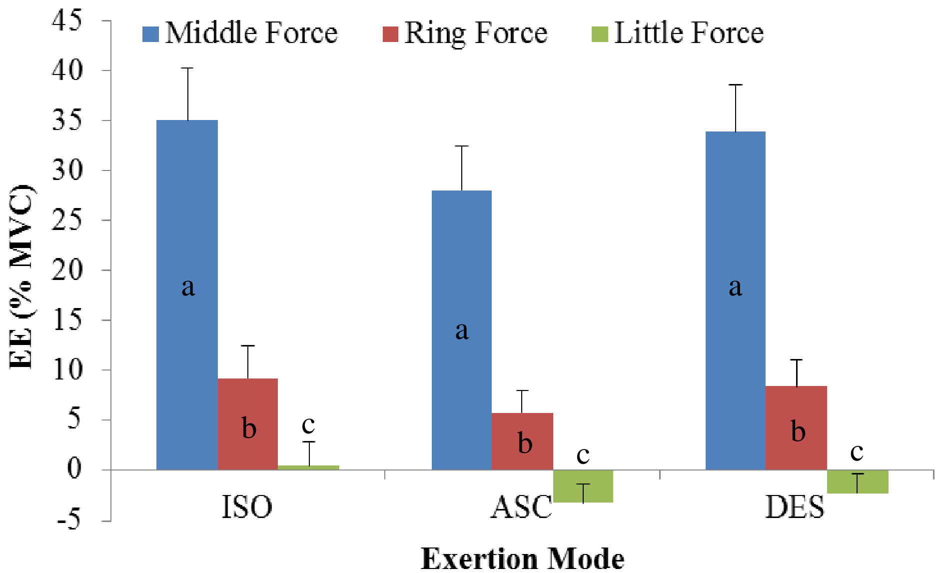


Figure 3.3. Summary of enslaving forces during isotonic exertions.



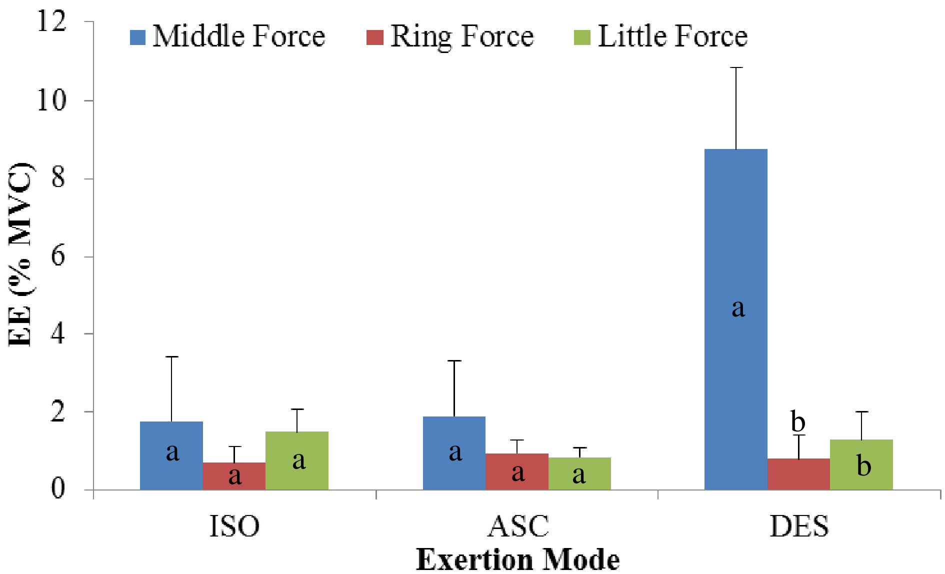
Middle Force
Ring Force
Little Force
EE (% MVC)
30
25
20
15
10
5
0
-5
a
b
c
ISO
ASC
DES
Exertion Mode

a)



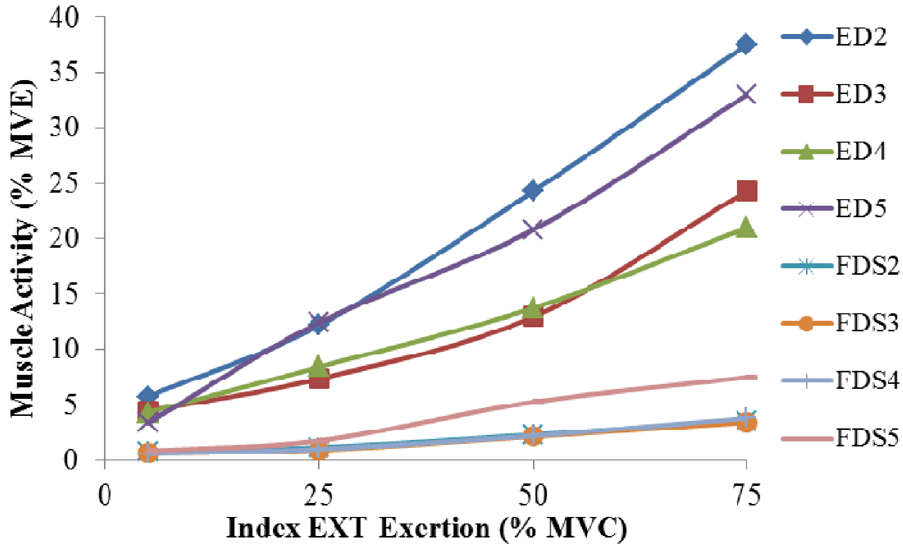
Middle Force
Ring Force
Little Force
EE (% MVC)
45
40
35
30
25
20
15
10
5
0
-5
a
b
c
ISO
ASC
DES
Exertion Mode

b)

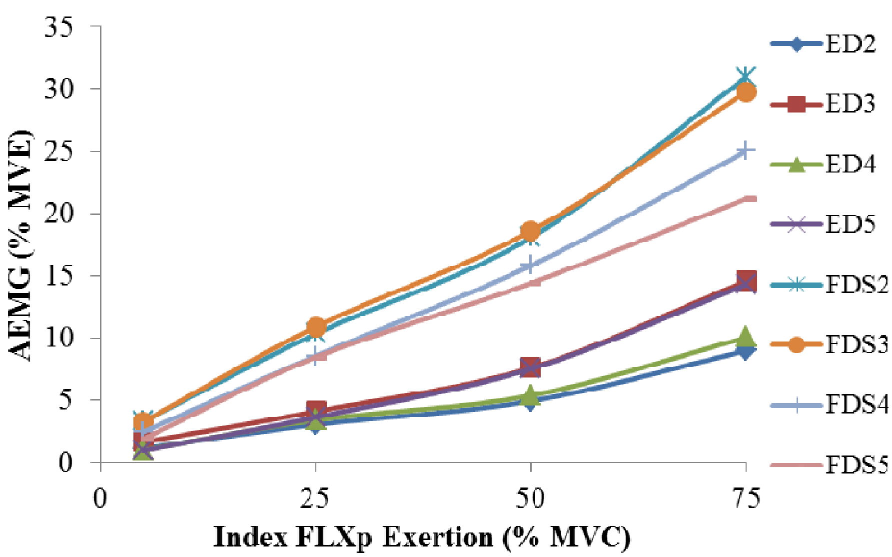


c)

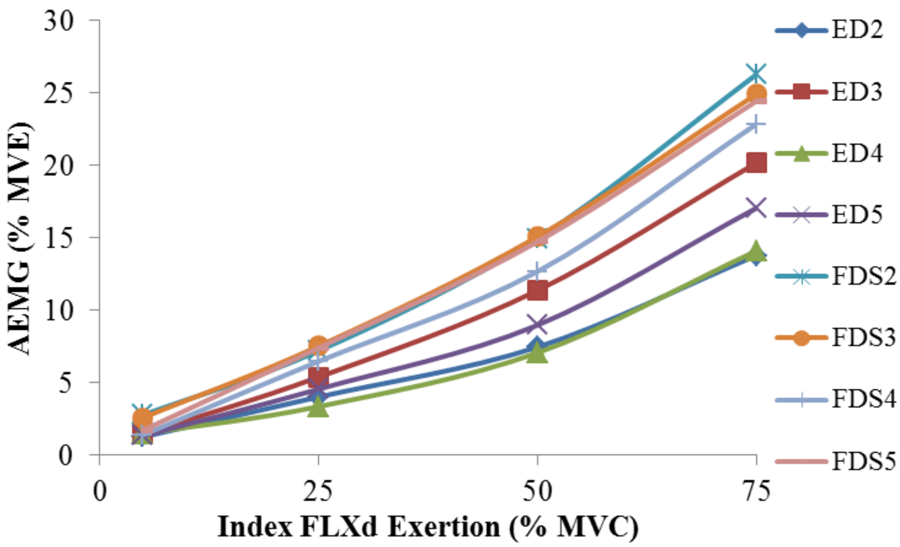
Figure 3.4. EE during index finger EXT exertion at (a) 50, (b) 75% MVC and (c) FLXd exertion at 50% MVC.


Muscle Activity (% MVE)
40
35
30
25
20
15
10
5
0
0
25
50
75
Index EXT Exertion (% MVC)
ED2
ED3
ED4
ED5
FDS2
FDS3
FDS4
FDS5

a)

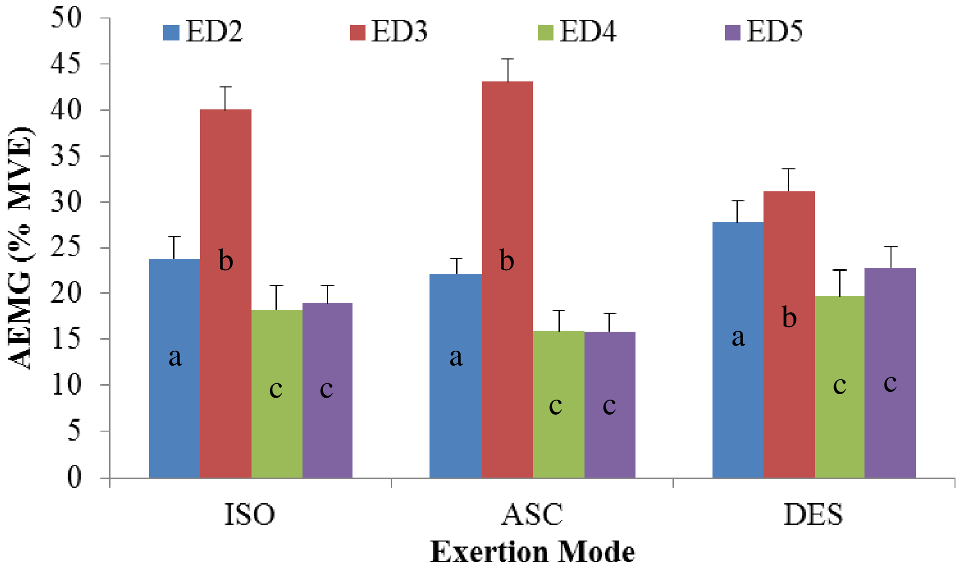

AEMG (% MVE)
35
30
25
20
15
10
5
0
0
25
50
75
Index FLXp Exertion (% MVC)
ED2
ED3
ED4
ED5
FDS2
FDS3
FDS4
FDS5

b)

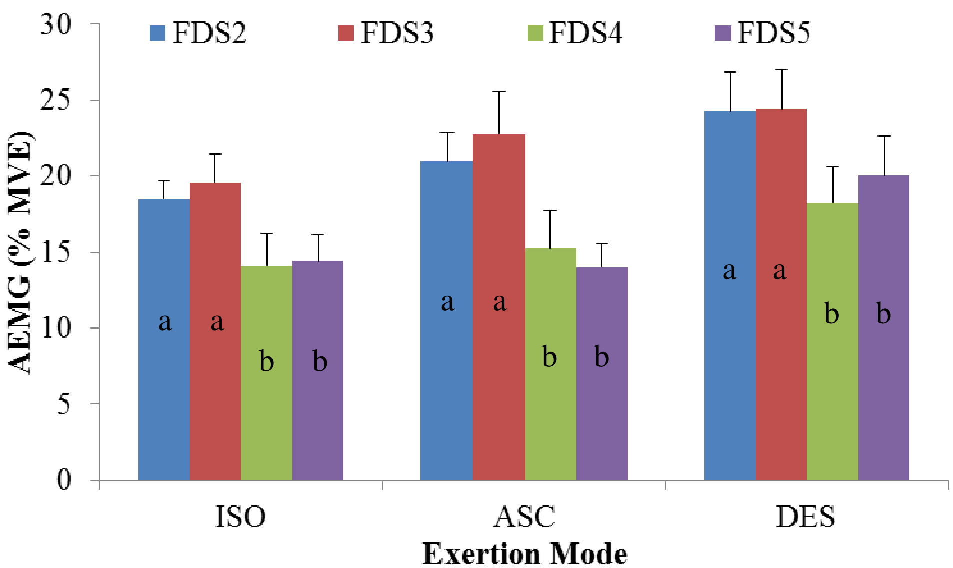


c)

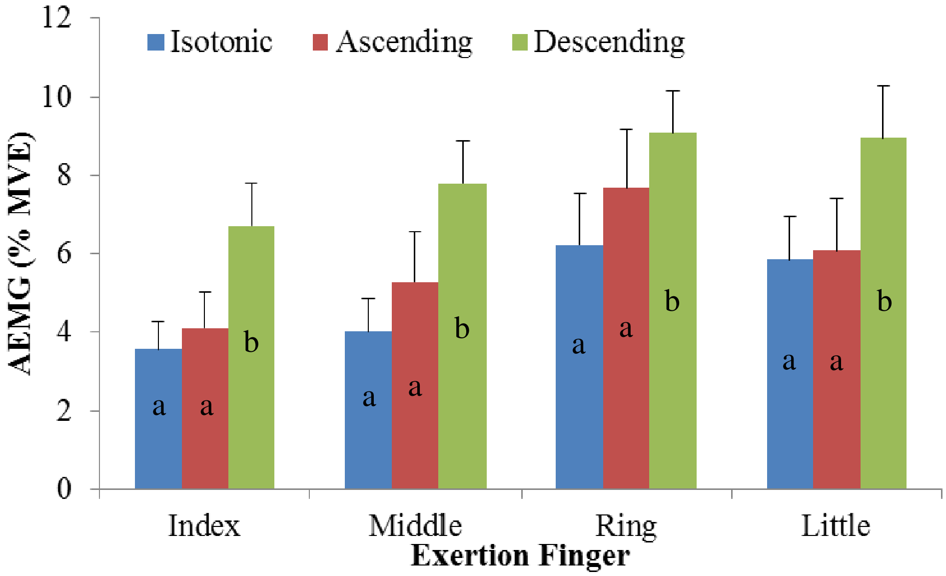
Figure 3.5. AEMG of all ED and FDS compartments during isotonic exertions of the index finger at all 4 exertion levels in (a) EXT, (b) FLXp and (c) FLXd.


ED2
ED3
ED4
ED5
AEMG (% MVE)
0
5
10
15
20
25
30
35
40
45
50
a
b
c
c
a
b
c
c
a
b
c
c
ISO
ASC
DES
Exertion Mode

a)


FDS2
FDS3
FDS4
FDS5
AEMG (% MVE)
0
5
10
15
20
25
30
a
a
b
b
a
a
b
b
a
a
b
b
ISO
ASC
DES
Exertion Mode

b)



c)

Figure 3.6. (a) ED AEMG in EXT and (b) FDS AEMG in FLXd exertions of middle finger at 50% MVC. (c) Mean of all 4 antagonist ED compartments during 25% MVC FLXp exertions of all fingers.

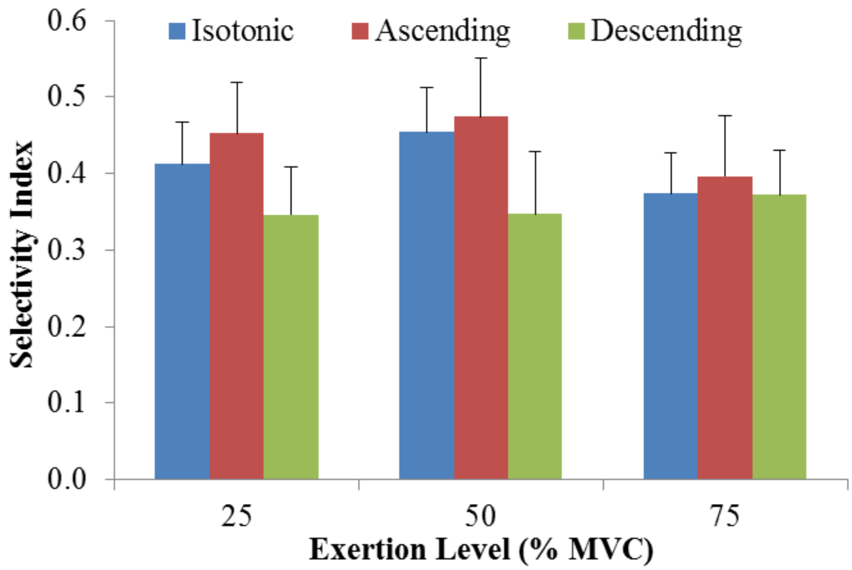
CHAPTER 4 – THESIS SUMMARY AND FUTURE DIRECTIONS

4.1. Thesis Summary

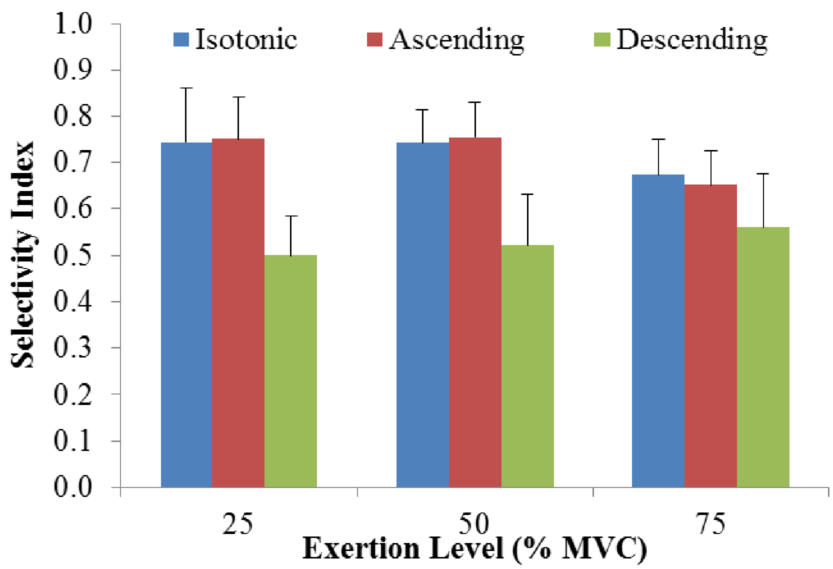
The mechanisms involved in finger control and independence is the subject of continuing research. The different aspects of independent movement and force production of fingers have been discussed previously with the primary focus on mechanical and neural factors contributing to the lack of finger independence. The current study provides further insight into the mechanisms involved in finger control by simultaneously measuring and recording both forces from all fingers and muscular activities of all the compartments of the extrinsic finger extensors (ED) and flexors (FDS) acting on individual fingers during various isometric exertions. This study represents the first attempt at using surface EMG to record the activity of all 8 compartments simultaneously. Furthermore, we investigated the contribution of the antagonist muscular compartments to joint stability and controlling the involuntary force production in the fingers. Finally, this study was the first to use 3 different isometric contraction modes (isotonic, ascending and descending) to examine whether the type of exertion affected the involuntary force production in fingers at different force levels.

We used several methods to quantify the involuntary force production in the fingers. First, we used the enslaving phenomenon (Zatsiorsky et al., 1998) which is also referred to as the enslaving effect (EE) or enslaving force. The enslaving effect is the force of the non-task fingers during the exertions of the task finger. EE allows us to compare the effect that the task finger has on all the non-task fingers individually. The second method, the modified selectivity index (SI) uses the absolute fractional forces produced by each finger instead to calculate a number between 0 and 1 (Keen and Fuglevand, 2003). The selectivity index of 1 represents force produced only by one finger and selectivity index of 0 represents force produced equally across all the digits (Appendix C). The SI allows us to estimate how selective the fingers are in producing forces ranging from the ideal situation where the force is being produced exclusively by the task finger versus the not ideal case where force is being distributed equally on fingers. Due to the volume of the current data set and while most statistical analyses have been completed, detailed interpretation of the results was outside the scope of the current Master's thesis. Some of these results have been presented in the next few paragraphs as a point of comparison between the different analysis methods and as an aid in explaining some of the findings presented in the previous chapter.

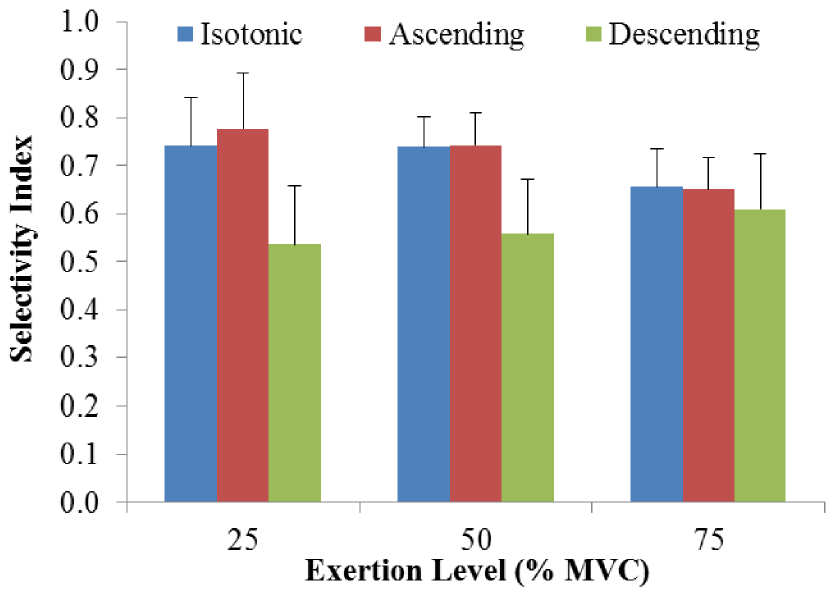
One of the major findings of the current study was that the exertion mode only affected the enslaving forces and the average EMG of the muscular compartments less than or equal to 50% MVC. The enslaving forces were greater, and the non-task muscular compartments had higher activity, during descending exertions compared to the isotonic and ascending exertion modes. We found similar trends in SI compared to EE. The SI was lower (less selective force production) during the descending exertions compared to the isotonic and ascending exertions at 25 and 50% MVC force levels (Figure 4.1). At 75% MVC, the SI was similar between the 3 exertion modes (Figure 4.1). Also, the SI was higher during extension compared to flexion exertions quantifying less selective force production during extension exertions (Figure 4.1a vs. 4.1b and c). An advantage of using SI over EE is that the use of fractional forces (each finger as a fraction of the total force) instead of the absolute forces (of each finger individually) in EE allowed us to directly compare the selectivity of fingers at different force levels. For the isotonic and ascending exertions, the SI was higher at 25 and 50% MVC than 75% MVC but similar during all 3 exertion levels of descending contractions during both flexion and extension exertions (Figure 4.1). A disadvantage of using SI compared to EE is that we cannot make any comparisons between the involuntary forces being produced by the non-task fingers as a function of the proximity to the task fingers.



a)



b)



c)

Figure 4.1. Selectivity index (Mean ± SE) during ring finger (a) EXT, (b) FLXp and (c) FLXd exertions.

Another finding of the current study was that both the EE and AEMG of the adjacent fingers and non-task compartments were higher than the non-adjacent fingers and non-task compartments. Not surprisingly, the adjacent compartments generally had higher cross correlation values (Appendix C) than non-adjacent compartments (Table 4.1). For the extensor compartments, the peak cross correlation values did not change with the increase in the exertion level (Table 4.1a). Since both the enslaving forces and muscle activity of the non-task compartments increased with the increase in the exertion force of the task finger, the consistency in the cross correlation values among different exertion levels could be partially attributed to crosstalk between the electrodes. We also found a significant linear relationship between the AEMG of the extensors and the exertion level (Figure 3.5a). Therefore, another explanation for the observed consistency in the amount of common signal (cross correlation) among the extensors could be that a high level of consistency exists in the descending motor commands (to the extensors) which are modulated based on force. The cross correlation values of the flexors were not consistent among the different exertion levels (Table 4.2b). Unlike our AEMG results which showed similar and significantly higher activity in FDS2 and FDS3 during middle finger exertions (Figure 3.6b), we found the highest cross correlations (during middle finger exertions) between FDS3 and FDS4 which was up to double the peak cross correlation between FDS2 and FDS3 (0.72 vs. 0.36, respectively, at 75% MVC). The discrepancy between the AEMG and the cross correlation results can be partially due to crosstalk between the electrodes. The enslaving forces were also significantly higher in the ring finger compared to the index finger during FLXd middle finger exertions. Therefore, it is likely that neural coupling between FDS3 and FDS4 motor units resulted not only in the high cross correlation values between these two compartments but also greater enslaving forces in the ring finger.

Table 4.1. The peak cross correlation values (mean of 12 subjects) between a) the extensor compartment during EXT and b) the flexor compartments during FLXd exertions at 25, 50 and 75% MVC. The task compartments on the left side of the table were compared to all the other compartments listed across the top of the table.

a) EXT

25% MVC				
	ED2	ED3	ED4	ED5
ED2		0.46	0.36	0.27
ED3	0.52		0.47	0.33
ED4	0.40	0.39		0.33
ED5	0.33	0.31	0.39	
50% MVC				
	ED2	ED3	ED4	ED5
ED2		0.47	0.34	0.25
ED3	0.51		0.43	0.31
ED4	0.35	0.40		0.37
ED5	0.31	0.30	0.42	
75% MVC				
	ED2	ED3	ED4	ED5
ED2		0.48	0.35	0.26
ED3	0.48		0.41	0.29
ED4	0.39	0.42		0.35
ED5	0.30	0.31	0.39	

b) FLXd

25% MVC				
	FDS2	FDS3	FDS4	FDS5
FDS2		0.23	0.30	0.20
FDS3	0.44		0.74	-0.06
FDS4	0.09	0.63		0.14
FDS5	0.32	0.12	0.69	
50% MVC				
	FDS2	FDS3	FDS4	FDS5
FDS2		0.24	0.11	0.41
FDS3	0.48		0.71	-0.31
FDS4	0.10	0.66		0.33
FDS5	0.10	0.00	0.64	
75% MVC				
	FDS2	FDS3	FDS4	FDS5
FDS2		0.54	0.03	0.38
FDS3	0.36		0.72	-0.33
FDS4	0.01	0.61		0.60
FDS5	0.13	0.07	0.66	

The activity of the antagonist extensor compartments were much higher during flexion exertions compared to the activity of the flexor compartments during extension exertions. The functional co-contraction of the extensors during flexion exertions likely contributes to joint stability and at least partially counterbalances the involuntary activation of the non-task flexor compartments resulting in lower enslaving forces in flexion compared to extension exertions. There are other factors contributing to the greater enslaving forces in extension versus flexion exertions. First, it has been suggested that the descending motor commands to the FDS muscle might be more selective for the subgroup of motor neurons acting on individual compartments compared to those of both ED and FDP muscles (Butler et al., 2005). Second, the degree of synchronous firing of motor units of the adjacent ED compartments was lower than those of the adjacent FDS compartments (with the exception of ED2-ED3) during weak extension and flexion exertions respectively (Keen and Fuglevand, 2004; McIsaac and Fuglevand, 2007). Third, interconnection between the tendons of the ED compartments (juncturae intertendinei) results in mechanical coupling and tension transmission between the extensor tendons (Schieber and Santello, 2004). These interconnections do not exist between FDS tendons. Finally, the existence of motor units acting on more than one compartment (multi-digit motor units) have been suggested and statistically shown in both ED and the deep flexors (FDP) but not FDS.

In general, we also found the activity of the extensors to be higher than flexors during the extension and flexion exertion respectively. There are several explanations for the higher activity of the extensors. First, there are 2 extrinsic finger flexor muscle groups, the FDS and FDP serving each finger. It was not possible to record the activity of the deep flexors using surface EMG. Since FDP compartments contribute to finger flexion force production, the recorded FDS activity in our study only partially reflects the contribution of the extrinsic flexor apparatus in producing forces on individual fingers. Second, the extrinsic extensors have smaller moment arms than the flexors. Also, the rings were placed more distal along the fingers for the flexion trials compared to the extension trials (mid proximal phalanges in EXT versus mid-point of middle and distal phalanges in FLXp and FLXd). Taken together, the extensors likely had to have higher activity in order to produce the same moment of force compared to the flexors. Lastly, the high cross correlation values between the flexor compartments during flexion exertions can be attributed to one of the study limitations. While careful functional and anatomical testing was employed prior to electrode placement, the present study was the first attempt (to our knowledge) using surface EMG to determine the activity of the individual compartments of FDS. Previous research (Leijnse et al., 2008b) was used as a guideline in electrode placements of the ED compartments. Thus, the lower cross correlation values in extension may be due to lower crosstalk between the adjacent electrode pairs and reflect more accurate EMG recordings from the individual extensor compartments compared to the flexor compartments.

4.2. Conclusion and Future Directions

The type of exertion affected the involuntary force production and extrinsic finger extensor and flexor compartment activation but only in low to mid-range exertions. Among the 3 exertion modes investigated in the present study, the descending isometric exertions proved to be the most challenging for the neuromuscular apparatus of the hand in terms of finger control. Proximity to the task finger and muscular compartment serving the task finger affected force production and muscle activation in the non-intended fingers and muscular compartments at all force levels. Future studies should focus more on the different exertion types and investigate the possibility of different mechanisms being involved in finger control at different force levels. Our subjects often reported difficulty during the descending phase of the triangular exertions and sometimes decreased the finger forces more gradually than the instructed duration of 4.5 seconds. Experimental procedures with different triangular exertion durations are needed in order to determine a duration that would both improve the accuracy of force production and decrease the difficulty of the task.

In general, the fingers were less independent in exerting force in extension versus flexion. Interestingly, we also found higher activity in the antagonist extrinsic finger extensors during flexion exertions compared to the activity of the flexors during extension exertions. Functionally, the co-activation of the antagonist extensors stabilizes the joints and may have counterbalanced the involuntary activation of the superficial finger flexors. In order to better identify the mechanisms in which the antagonist muscles are involved in finger control, the activity of the deep flexors and the intrinsic muscles have to be investigated as well. Also, we found high cross correlation values between the flexor compartments and to a lesser extent the extensor compartments partially due to crosstalk between the electrodes. The use of indwelling electrodes would likely decrease the crosstalk between the electrodes. Imaging techniques (such as ultrasound) can also be used in order to landmark the muscle bellies of individual compartments for each subject prior to collection.

REFERENCES

Au AK, Keir PJ. Interfering effects of multitasking on muscle activity in the upper extremity. J Electromyogr Kinesiol 2007;17(5):578-586.

Burgar CG, Valero-Cuevas FJ, and Hentz VR. Fine-wire electromyographic recording during force generation. Application to index finger kinesiologic studies. Am J Phys Med Rehabil 1997;76(6):494-501.

Butler TJ, Kilbreath SL, Gorman RB, and Gandevia SC. Selective recruitment of single motor units in human flexor digitorum superficialis muscle during flexion of individual fingers. J Physiol 2005;567(Pt 1):301-9.

Danion F, Li S, Zatsiorsky VM, and Latash ML. Relations between surface EMG of extrinsic flexors and individual finger forces support the notion of muscle compartments. Eur J Appl Physiol 2002;88(1-2):185-8.

Kaplan, EB. Anatomy, injuries and treatment of the extensor apparatus of the hand. Clinic Orthop 1959;13:24-41.

Keen DA, Fuglevand AJ. Role of intertendinous connections in distribution of force in the human extensor digitorum muscle. Muscle Nerve 2003;28(5):614-22.

Keen DA and Fuglevand AJ. Common input to motor neurons innervating the same and different compartments of the human extensor digitorum muscle. J Neurophysiol 2004;91(1):57-62.

Kilbreath SL, Gandevia SC. Limited independent flexion of the thumb and fingers in human subjects. J Physiol 1994;479 (Pt 3):487-97.

Kilbreath SL, Gorman RB, Raymond J, Gandevia SC. Distribution of the forces produced by motor unit activity in the human flexor digitorum profundus. J Physiol 2002;543(1):289-296.

Leijnse, JN. Measuring force transfers in the deep flexors of the musicians hand: theoretical analysis, clinical examples. J Biomechanics 1997;30(9):873-882.

Leijnse JN, Campbell-Kyureghyan NH, Spektor D, and Quesada PM. Assessment of individual finger muscle activity in the extensor digitorum communis by surface EMG. J Neurophysiol 2008a;100(6):3225-35.

Leijnse JN, Carter S, Gupta A, and McCabe S. Anatomic basis for individuated surface EMG and homogeneous electrostimulation with neuroprostheses of the extensor digitorum communis. J Neurophysiol 2008b;100(1):64-75.

Li ZM, Zatsiorsky VM, and Latash ML. Contribution of the extrinsic and intrinsic hand muscles to the moments in finger joints. Clin Biomech (Bristol , Avon) 2000;15(3):203-11.

Maier MA, Hepp-Reymond MC. EMG activation patterns during force production in precision grip. I. Contribution of 15 finger muscles to isometric force. Exp Brain Res 1995a;103(1):108-22.

Maier MA, Hepp-Reymond MC. EMG activation patterns during force production in precision grip. II. Muscular synergies in the spatial and temporal domain. Exp Brain Res 1995b;103(1):123-36.

McIsaac TL, Fuglevand AJ. Motor-unit synchrony within and across compartments of the human flexor digitorum superficialis. J Neurophysiol 2007;97(1):550-6.

Mogk JP, Keir PJ. Crosstalk in surface electromyography of the proximal forearm during gripping tasks. J Electromyogr Kinesiol 2003;13(1):63-71.

Perotto AO, Delagi EF, Iazzetti J, Morrison D. Anatomical guide for the electromyographer: The limbs and trunk. 4th ed. Illinois: Charles C Thomas, 2004.

Reilly KT, Hammond GR. Independence of force production by digits of the human hand. Neurosci Lett 2000;290(1):53-6.

Reilly KT, Schieber MH. Incomplete functional subdivision of the human multitendoned finger muscle flexor digitorum profundus: an electromyographic study. J Neurophysiol 2003;90(4):2560-70.

Reilly KT, Nordstrom MA, and Schieber MH. Short-term synchronization between motor units in different functional subdivisions of the human flexor digitorum profundus muscle. J Neurophysiol 2004;92(2):734-42.

Robinson TL, Fuglevand AJ. Independence of finger movements in normal subjects and in concert level pianists. Soc Neurosci Abstr 1999;25:1149.

Rufener EA, Hepp-Reymond MC. Muscle coactivation patterns in the precision grip. Adv Biosci 1988;70:169-72.

Schieber MH, Hibbard LS. How somatotopic is the motor cortex hand area? Science 1993;261(5120):489-92.

Schieber MH, Gardinier J, Liu J. Tension distribution to the five digits of the hand by neuromuscular compartments in the macaque flexor digitorum profundus. J Neurosci 2001,21(6):2150-2158.

Schieber MH, Santello M. Hand function: peripheral and central constraints on performance. J Appl Physiol 2004;96(6):2293-300.

Schuenke M, Schulte E, Schumacher U. Thieme atlas of anatomy: general anatomy and musculoskeletal system. 3rd ed. New Jersey: Icon Learning System, 2003.

Shim JK, Olafsdottir H, Zatsiorsky VM, and Latash ML. The emergence and disappearance of multi-digit synergies during force-production tasks. Exp Brain Res 2005;164(2):260-70.

Slobounov S, Johnston J, Chiang H, and Ray W. The role of sub-maximal force production in the enslaving phenomenon. Brain Res 2002a;954(2):212-9.

Slobounov S, Chiang H, Johnston J, and Ray W. Modulated cortical control of individual fingers in experienced musicians: an EEG study. Electroencephalographic study. Clin Neurophysiol 2002b;113(12):2013-24.

Tortora GJ, Grabowski SR. Principles of anatomy and physiology. 10th ed. New Jersey: John Wiley and Sons, Inc., 2003.

Valero-Cuevas FJ. Predictive modulation of muscle coordination pattern magnitude scales fingertip force magnitude over the voluntary range. J Neurophysiol 2000;83(3):1469-79.

Valero-Cuevas FJ. An integrative approach to the biomechanical function and neuromuscular control of the fingers. J Biomech 2005;38(4):673-84.

Valero-Cuevas FJ. Why the hand? Adv Exp Med Biol 2009;629:553-7.

van Duinen DH, Yu WS, and Gandevia SC. Limited ability to extend the digits of the human hand independently with extensor digitorum. J Physiol 2009;587(Pt 20):4799-810.

von Schroeder HP, Botte MJ, and Gellman H. Anatomy of the juncturae tendinum of the hand. J Hand Surg Am 1990;15(4):595-602.

Winter DA, Patla AE. Signal processing and linear systems for the movement science. Ontario: Waterloo Biomechanics, 1997.

Zatsiorsky VM, Li ZM, and Latash ML. Coordinated force production in multi-finger tasks: finger interaction and neural network modeling. Biol Cybern 1998;79(2):139-50.

Zatsiorsky VM, Li ZM, and Latash ML. Enslaving effects in multi-finger force production. Exp Brain Res 2000;131(2):187-95.

APPENDIX A: Selectivity Index

The selectivity index (SI) was calculated from the forces produced on each finger using the following formulae (Keen and Fuglevand, 2003):

$$d - \sqrt{\sum_{i=1}^{n}(\tau_i - \tau_u)^2} \qquad (1)$$

$$d_{max} = \sqrt{(1-\tau_u)^2 + \sum_{i=2}^{n}(\tau_u)^2} \qquad (2)$$

$$Selectivity\ Index = \frac{d}{d_{max}} \qquad (3)$$

- τ_I: fraction of force produced by each finger (force produced by a digit divided by total force produced from all digits);
    - Modified selectivity index: absolute forces were used instead of directional forces
- τ_u: 1.0 divided by the number of tendons emerging from the muscle (in this case 4 tendons, $\tau_u = 0.25$);
- d_{max}: the difference between an ideally selective force production (force produced on one finger only) and an ideally unselective force production (force produced equally on all fingers);
- d: the difference between the force produced by each finger and an ideally unselective force production.
- Since τ_u has a constant value of 0.25, $d_{max} = 0.866$.
- Selectivity index: "d" divided by "d_{max}", ranges from 0 to 1.
- SI = 1 represents force produced only by one finger; SI = 0 represents force produced equally across all the digits.

APPENDIX B: Cross Correlation

The cross correlation function was used to compute the common signal. The cross correlation values were calculated between all 12 channels for a total of 66 comparisons. Raw and filtered (LE at 3 Hz) EMG signals were used (separately) to calculate the cross correlation coefficients. The cross correlation is calculated as (Winter and Patla, 1997):

$$R_{xy}\,(\theta) = \frac{\frac{1}{T}\int_0^T x(t)y(t-\theta)\,dt}{\sqrt{R_{xx}(0)\times R_{yy}(0)}} \tag{4}$$

- where x(t) and y(t) are the signals being correlated,
- T is the length of the signals,
- θ is the time shift,
- $R_{xx}(0)$ and $R_{yy}(0)$ are the auto correlations of x(t) and y(t) at θ=0,
- $R_{xy}(\theta)$ is the normalized cross correlation value,
- For the cross correlation value to be between -1 and 1, the mean of signals x(t) and y(t) has to be zero. Therefore, the mean of x(t) and y(t) was calculated and subtracted from the signal prior to using this formula.

APPENDIX C. Ethics Approval and Consent Form

14/12/2009 MREB Approval Certificate

McMaster University Research Ethics Board (MREB)

c/o Office of Research Services, MREB Secretariat, GH-305, e-mail: ethicsoffice@mcmaster.ca

CERTIFICATE OF ETHICS CLEARANCE TO INVOLVE HUMAN PARTICIPANTS IN RESEARCH

Application Status: New ☐ **Addendum** ☑ **Renewal** ☐ **Project Number** 2007 148

TITLE OF RESEARCH PROJECT:

Activity and force from "non-active fingers"

Faculty Investigator(s)/ Supervisor(s)	Dept./Address	Phone	E-Mail
P. Keir	Kinesiology	23543	pjkeir@mcmaster.ca
Student Investigator(s)	**Dept./Address**	**Phone**	**E-Mail**
K. Sanei	Kinesiology		saneik@mcmaster.ca

The application in support of the above research project has been reviewed by the MREB to ensure compliance with the Tri-Council Policy Statement and the McMaster University Policies and Guidelines for Research Involving Human Participants. The following ethics certification is provided by the MREB:

☐ The application protocol is approved as presented without questions or requests for modification.

☐ The application protocol is approved as revised without questions or requests for modification.

☐ The application protocol is approved subject to clarification and/or modification as appended or identified below:

COMMENTS AND CONDITIONS:Ongoing approval is contingent on completing the annual completed/status report. A "Change Request" or amendment must be made and approved before any alterations are made to the research.

Reporting Frequency: **Annual:** Jan-07-2010 **Other:**

Date: Jan-07-2008 **Co-Chairs, Dr. D. Maurer, Dr. D. Pawluch:**

...mcmaster.ca/.../print_approval_FF.cfm?... 1/1

December 12, 2009

Letter of Information and Consent

The "connectedness" of fingers. Activity and force from "non-active fingers"

Investigators: Kia Sanei and Dr. Peter Keir

Principal Investigator: Dr. Peter Keir
Department of Kinesiology
McMaster University
Hamilton, Ontario, Canada
(905) 525-9140 ext. 23543

Student / Co-Investigator Kia Sanei
Department of Kinesiology
McMaster University
Hamilton, Ontario, Canada
(905) 525-9140 ext. 21334

Purpose of the Study
When humans are asked to move a single finger or apply force voluntarily with a single finger, movement and/or force tends to be produced by the other fingers as well. The purpose of this study is to investigate the degree of finger independence during static finger efforts.

Procedures involved in the Research
After introducing you to the apparatus and protocol, anthropometric measures (height, weight, arm and hand length) will be recorded. Immediately following this you will have recording electrodes placed over 8 muscles of the forearm. These electrodes allow us to record the activity in the muscles that control your fingers. To know how active your muscles are, we first need to determine the maximum activity for each muscle through a series of tests for each muscle. The apparatus will be placed on an adjustable table to measure individual finger forces. There will be padding on the table for your elbow and wrist. For the protocol, you will be seated with your forearm secured on top of the table so that your elbow is at 120 degrees of flexion, your thumb is pointing up and your wrist is in neutral posture with no flexion/extension or side bending. You will be required to statically exert finger flexion and extension forces by placing fingers in 4 padded finger force testing device. Finger flexion and extension exertions will be performed at different levels of force ranging from 0 to 100 percent of your maximum finger force. The duration of the flexion and extension exertions will be 5 to 20 seconds for each finger with 10 to 40 seconds of rest between consecutive exertions of the same finger. Your participation will require about 2 hours in the lab.

Potential Harms, Risks or Discomforts:
There is minimal risk associated with participation in this study. You may experience some muscle soreness as a result of the maximal exertions. Although very rare, you may experience a temporary reaction to the adhesive from the surface electrodes. Should you experience any serious discomfort following the study, please contact the principal investigator, Dr. Peter Keir. Due to the nature of the protocol, you will not be allowed to participate if you have been diagnosed with high blood pressure or have previous shoulder and wrist injuries.

Potential Benefits
We hope to understand the degree of finger independence in both flexion and extension and the possible mechanisms related to the lack of independent finger movement and involuntary force production in the fingers. The research will not benefit you directly.

Payment or Reimbursement:
You will be financially compensated $20 for your time and participation in this study.

Confidentiality:
Your identity will be kept confidential; it will not be connected to your data, which will be used for teaching and research purposes only. The information directly pertaining to you will be locked in a cabinet for a maximum of 15 years.
You may be asked if you would be willing to have photos or video of you taken for use in publications and presentations. Photo and video data will only be used with your consent. Your name will not be associated with the images but someone viewing them might recognize your identity.

Participation:
Your participation in this study is voluntary. If you decide to participate, you can decide to stop at any time, even after signing the consent form or part-way through the study. If you drop out of the study, your data will only be used with your explicit consent. If you decide to stop participating, there will be no consequences to you and the compensation will be prorated. If you do not want to answer some of the questions you do not have to, but you can still be in the study.

Information About the Study Results:
You may obtain information about the results of the study by contacting Dr. Keir or Kia Sanei. An update will be emailed after completion of the study; if you would like an update your email will be required.

Information about Participating as a Study Subject:
If you have questions or require more information about the study itself, please contact Dr. Keir or Kia Sanei.

This study has been reviewed and approved by the McMaster Research Ethics Board. If you have concerns or questions about your rights as a participant or about the way the study is conducted, you may contact:

McMaster Research Ethics Board Secretariat
Telephone: (905) 525-9140 ext. 23142
c/o Office of Research Services
E-mail: ethicsoffice@mcmaster.ca

Note: Consent and signature sections are located on the following page.

CONSENT

I have read the information presented in the information letter about a study being conducted by Kia Sanei and Dr. Keir, of McMaster University. I have had the opportunity to ask questions about my involvement in this study, and to receive any additional details I wanted to know about the study. I understand that I may withdraw from the study at any time, if I choose to do so, and I agree to participate in this study. I have been given a copy of this form.

____________________________________ ____________________________________

Name of Participant Signature of Participant

I agree to allow the optional photos and videos of me to be taken during the task.

Photo

Yes _____
No ______
Videos

Yes______
No_______

____

Signature of Participant

In my opinion, the person who has signed above is agreeing to participate in this study voluntarily, and understands the nature of the study and the consequences of participation in it.

____
Signature of Researcher or Witness