QUANTIFYING THE CONTRIBUTION OF PASSIVE STRUCTURES IN FINGER INDEPENDENCE

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ABSTRACT

Mechanical and neural factors have been suggested to limit finger independence. Fingers producing involuntary movement or force production during intended actions of another finger are considered “enslaved” to that finger. The purpose of this thesis was to quantify the contribution of passive mechanical factors to this enslaving effect, in particular, the contributions of the intertendinous connections between extensor tendons. Twenty participants (10 men, 10 women) performed *Master* and *Slave Tasks* in three wrist (30° extension, neutral, 30° flexion) and two metacarpophalangeal (MCP) (straight and 90° flexion) postures. During the *Master Task,* the ring finger was the intended or “master” finger. Three 10 s isometric ring finger extensions were performed at 25% of maximum voluntary contraction. Finger force and surface electromyography of the 4 extensor digitorum (ED) bellies were recorded. In the *Slave Tasks,* the middle and little fingers (“slave” fingers during the *Master Task*) each performed three 10 s isometric finger extensions at their mean activation levels during the *Master Task.* Hypothetical mechanical contribution (HMC) was determined for the middle and little fingers. The HMC was defined as the difference between the involuntary force (from the *Master Task*) and the voluntary force (from the *Slave Task*) relative to the involuntary force. A small proportion of the HMC values (Middle: 39%; Little: 15%) were within the expected range of 0 to 100%, suggesting that the equation developed in this study provided a limited representation of the contribution of passive intertendinous structures. Index finger forces increased with MCP flexion, suggesting the importance of juncturae tendineii in finger independence. Higher ED activity during wrist extension, than neutral or flexed postures, with straight MCP supports previous evidence in the literature. The complex phenomenon of enslaving in different wrist and MCP positions warrants further research for quantifying the mechanical contribution in finger independence.

Keywords: Surface electromyography, intertendinous connections, enslaving, finger force, finger independence

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Contributions

This study was conceived by Kumara G. Somasundram and Dr. Peter J. Keir. Method development, data collection and analysis, interpretation of results, and preparation of manuscript were completed by Kumara Somasundram, with oversight and input from Dr. Keir.

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LIST OF ABBREVIATIONS

CNS	Central nervous system
DIP	Distal interphalangeal
ED	Extensor digitorum
EMG	Electromyography
FDP	Flexor digitorum profundus
FDS	Flexor digitorum superficialis
HMC	Hypothetical mechanical contribution
M1	Primary motor cortex
MCP	Metacarpophalangeal
MVC	Maximum voluntary contraction
MVE	Maximum voluntary excitation
PIP	Proximal interphalangeal

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CHAPTER 1: INTRODUCTION

Finger control is essential for performing activities of daily living and workplace tasks such as typing, writing, and handling tools. The intricate structure of the hand includes muscles, ligaments, and connective tissues, which function together for finger control. However, fingers do not act completely independently. Movement or force production of one finger causes other digits to move or generate force involuntarily (Zatsiorsky et al., 2000; Sanei & Keir, 2013; van Beek et al., 2018; May & Keir, 2018). The phenomenon of involuntary movement or force production is known as "enslaving" (Zatsiorsky et al., 2000). A lack of finger independence may affect an individual's dexterity and performance in manual tasks. For example, enslaving during typing may cause an individual to press an incorrect key unintentionally, hence, reducing accuracy. Therefore, a deeper understanding of the mechanisms that limit finger independence is crucial for creating strategies to improve finger control and rehabilitation.

Finger independence is limited by mechanical and neural factors. Mechanically, enslaving results from forces transmitted through juncturae tendineii (passive intertendinous connections) between the extrinsic finger extensor tendons (von Schroeder & Botte, 1993). Similarly, connective tissues between extrinsic finger flexor tendons and muscle bellies also transfers force across fingers, producing involuntary forces (Leijnse et al., 1997a). Neurally, the overlap of regions representing different finger movements in the primary motor cortex have been suggested to produce involuntary finger movement (Schieber and Hibbard, 1993). Moreover, synchronous firing of motor units in the muscle bellies of different extrinsic finger flexors (Winges & Santello, 2004; McIsaac &

Fuglevand, 2007) and extensors (Keen & Fuglevand, 2004) may partially explain the involuntary force production.

The contribution of passive intertendinous structures towards enslaving remains unclear. Juncturae tendineii have been shown to play a minor role in distributing force across fingers during intramuscular stimulation of finger extensors (Keen & Fuglevand, 2003). Additionally, May and Keir (2018) found higher involuntary finger forces and extensor muscle activity during finger extensions performed with an extended wrist compared to flexed and neutral postures. They expected higher involuntary forces in a flexed wrist due to the increased magnitude of passive force resulting from the stretched extensor tendons, transmitted via juncturae tendineii. Their findings may further suggest a minor contribution of intertendinous connections towards enslaving. Conversely, Lang & Schieber (2004) discovered that the magnitude of involuntary finger joint flexion-extension during passive finger flexion-extension was similar to active finger movements, indicating that intertendinous connections could be a primary contributor to enslaving. These conflicting findings warrant the need to further investigate the contribution of passive intertendinous structures towards limited finger independence.

The objective of this thesis was to quantify the contribution of passive intertendinous structures (juncturae tendineii) by analyzing the voluntary and involuntary forces at a given finger extensor activation level in different wrist and finger postures. By delineating the contribution of passive intertendinous structures, we may broaden our understanding of the mechanisms that limit finger independence, helping us develop better strategies for improving finger control.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Anatomy of the Finger

The hand consists of the thumb (digit 1) and four fingers (digits 2-5). Each finger includes four bone segments: metacarpal, proximal phalanx, middle phalanx, and distal phalanx; and three joints: metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) (Figure 2.1).

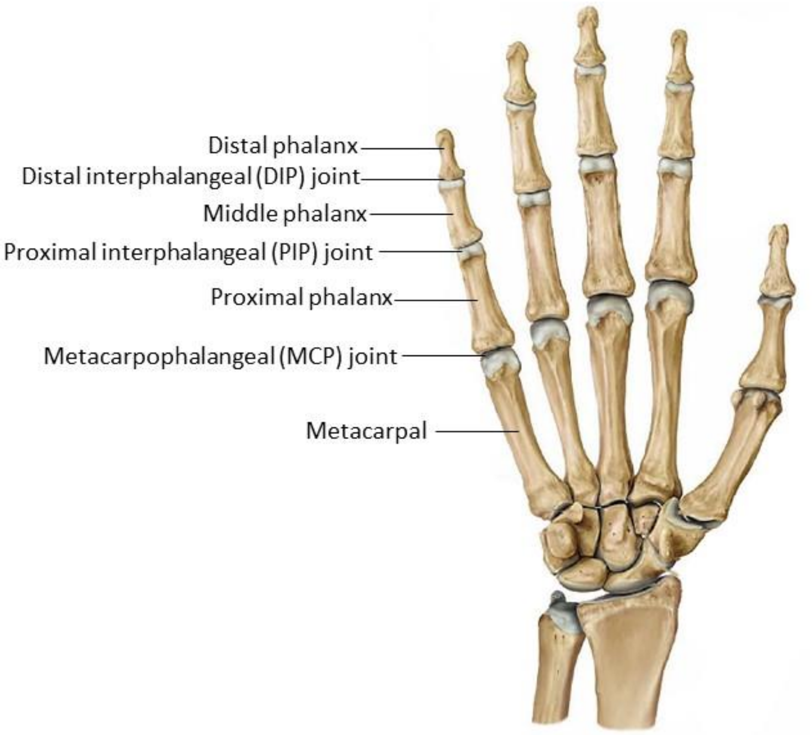


Figure 2.1: Palmar view of the right hand, identifying the phalanges (distal, middle, and proximal), metacarpal, and the finger joints (DIP, PIP, and MCP) (Schuenke et al., 2010).

Finger movements are controlled by muscles originating from the forearm (extrinsic muscles) and within the hand (intrinsic muscles). Extrinsic finger flexors include the flexor digitorum superficialis (FDS) and flexor digitorum profundus (FDP). FDS and FDP tendons insert on the middle and distal phalanx, respectively. FDS flexes the MCP, PIP, and wrist joints. FDP performs the same actions as FDS in addition to flexing the DIP joint. Connective tissues exist between the FDP tendons and muscle bellies (Malerich et al., 1987; Kilbreath and Gandevia, 1994; Leijnse et al., 1997b). These structures have been suggested to transmit force between the finger flexor muscles (Leijnse et al., 1997a; Schieber et al., 2001).

Extrinsic finger extensors include the extensor digitorum (ED), extensor indicis (EI), and extensor digiti minimi (EDM) (Figure 2.2). The extensor tendons insert on the extensor mechanism, a tendinous network that distributes forces generated by the extrinsic extensors and intrinsic muscles, along the dorsal surface of each finger (Garcia-Elias et al., 1991; Lee et al., 2008; MacIntosh & Keir, 2017). The ED extends the three joints of each finger, while EI and EDM function as additional extensors of the index and little finger, respectively. The extrinsic extensors extend the wrist as well. The ED tendons are interconnected by connective tissues known as juncturae tendineii (Figure 2.3), which functions to stabilize the ED tendons and maintain the spacing between them (von Schroeder et al., 1990; Greville Farrar & Kundra, 2012; Chinchalkar et al., 2015). These passive intertendinous structures have also been shown to transmit force across extensor tendons (von Schroeder & Botte, 1993; Keen and Fuglevand, 2003).

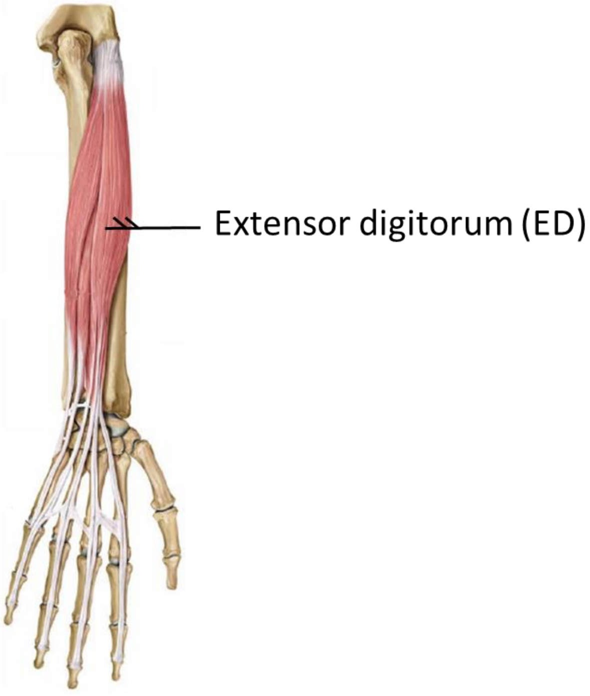


Figure 2.2: Dorsal view of the forearm, depicting the ED (Schuenke et al., 2010).

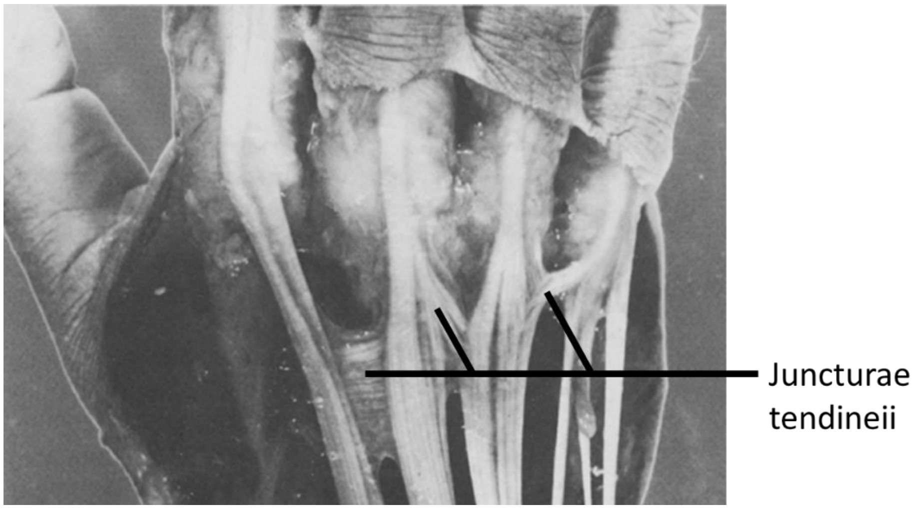


Figure 2.3: Dorsal view of a cadaveric hand, depicting the juncturae tendineii between the ED tendons (von Schroeder et al., 1990).

Digits are also controlled by intrinsic muscles such as the dorsal and palmar interossei, lumbricals, thenar, and hypothenar muscles. Lumbricals and interossei insert into the extensor mechanism of each finger and they flex the MCP as well as extend the PIP and DIP joints. The palmar and dorsal interossei also adduct and abduct the MCP, respectively. The thenar muscles (abductor pollicis brevis, adductor pollicis, flexor pollicis brevis, and opponens pollicis) insert on the thumb, enabling MCP flexion and carpometacarpal opposition. The hypothenar muscles (abductor digiti minimi, flexor digiti minimi brevis, and opponens digiti minimi) insert on the little finger and enable MCP flexion and abduction, in addition to DIP and PIP extension. The origin, insertion, and actions of the muscles controlling each finger are summarized in Table 2.1.

Table 2.1: Origins, insertions, and actions of extrinsic and intrinsic finger muscles summarized from Schuenke et al. (2010).

Muscle	Origin	Insertion	Action
	Extrinsic Finger Muscles		
Flexor digitorum profundus	Proximal two-thirds of ulna; Interosseus membrane	Distal phalanx of digits 2-5	Flexes wrist, MCP, PIP, and DIP
Flexor digitorum superficialis	Medial epicondyle of humerus; Coronoid process of ulna; Distal to radial tuberosity	Middle phalanx of digits 2-5	Flexes wrist, MCP, and PIP
Extensor digitorum	Lateral epicondyle of humerus	Extensor mechanism of digits 2-5	Extends wrist, MCP, PIP, and DIP
Extensor indicis	Posterior surface of ulna; Interosseus membrane	Extensor mechanism of digit 2	Extends wrist, MCP, PIP, and DIP
Extensor digiti minimi	Lateral epicondyle of humerus	Extensor mechanism of digit 5	Extends wrist, MCP, PIP, and DIP
	Intrinsic Finger Muscles		
Lumbricals	Radial side of FDP tendons of digit 2-5	Extensor mechanism of digit 2-5	Flexes MCP; Extends PIP and DIP;
Palmar interossei	Ulnar or radial side of MC 2, 4, and 5	Extensor mechanism of digit 2, 4, and 5	Flexes MCP; Extends PIP and DIP; Adducts MCP
Dorsal interossei	Ulnar and radial sides of MC 2-5	Extensor mechanism of digit 2-5	Flexes MCP; Extends PIP and DIP; Abducts MCP
Abductor digiti minimi	Pisiform	Ulnar base of proximal phalanx, and extensor mechanism of digit 5	Flexes MCP; Abducts MCP; Extends PIP and DIP
Flexor digiti minimi brevis	Hook of hamate; Flexor retinaculum	Proximal phalanx of digit 5	Flexes MCP
Opponens digiti minimi	Hook of hamate	Ulnar border of MC 5	Brings MC 5 towards thumb (opposition)

2.2 Mechanisms Limiting Finger Independence

Fingers are not capable of moving or producing force with complete independence. Movement or force production of a finger causes other digits to move or generate force involuntarily. For example, voluntary movement of one or multiple finger joints generates involuntary movement of the joints in other digits (Häger-Ross & Schieber, 2000; Li et al., 2004; Lang & Schieber, 2004; van den Noort et al., 2016; van Beek et al., 2018; Mirakhorlo et al., 2018). Similarly, during single-finger voluntary isometric pressing, other digits produce involuntary fingertip forces (Zatsiorsky et al., 2000; Sanei & Keir, 2013; May & Keir, 2018). This phenomenon of involuntary movement or force production is referred to as the "enslaving" (Zatsiorsky et al., 2000). The finger intended to generate movement or force is known as the "master" or "intended" finger, whereas the fingers producing involuntary movement or force are referred to as "slave" or "non-intended" fingers. The index finger has been shown to be most independent, whereas the ring finger is the least independent during both finger flexion (Zatsiorsky et al., 2000) and extension (Sanei & Keir, 2013). Flexion exertions produce lower involuntary forces than extensions exertions (Sanei & Keir, 2013), suggesting that fingers are more independent during flexion. The lack of finger independence has largely been attributed to both mechanical and neural factors but rarely delineated between them.

2.2.1 Mechanical Factors

Finger independence is limited by forces transferred via juncturae tendineii between the extrinsic finger extensor (ED) tendons. In a cadaveric study, von Schroeder and Botte (1993) pulled the individual extensor tendons and observed involuntary MCP, PIP, and DIP extension in the adjacent digits (von Schroeder & Botte, 1993). These involuntary movements were absent after the removal of juncturae tendineii. During intramuscular stimulation of ED, Keen & Fuglevand (2003) quantified the force distribution in the muscles using “selectivity index” based on the extension forces produced by each finger. A selectivity index of 1 indicates that forces generated from intramuscular stimulation were transmitted only to one finger, whereas an index of 0 represents an equal distribution of force across the four fingers. They found a mean selectivity index of 0.7, suggesting that intramuscular stimulation of ED transmitted forces primarily to one finger. This finding further suggested that although the juncturae tendineii is capable of distributing forces across fingers, the passive connections might have had a minor contribution towards the involuntary forces produced by the other fingers (Keen & Fuglevand, 2003).

The influence of connective tissues between deep finger flexors (FDP) on finger independence has also been investigated. Kilbreath and Gandevia (1994) passively rotated DIP joints in anesthetized forearms and discovered an absence of DIP movement in the adjacent “slave” fingers. Although this evidence might indicate that mechanical factors did not contribute towards enslaving, another finding from their study suggested otherwise. In a separate condition, participants actively rotated DIP joints individually at

5% of maximum voluntary contraction of the respective finger. The authors observed involuntary DIP movement in the adjacent “slave” digit, despite an absence of the FDP activity in the corresponding digit. This involuntary movement, however, was observed only occasionally. The authors did not report on the number of trials in which involuntary DIP movement was present. These equivocal findings from Kilbreath and Gandevia (1994) demonstrate a need to further examine the contribution of mechanical factors towards enslaving.

Several studies have examined the contribution of passive intertendinous connections by analyzing finger joint kinematics and surface electromyography (EMG). To quantify finger independence during passive and active single-finger MCP flexion-extension, Lang and Schieber (2004) calculated an “individuation index” (calculated as 1 minus the ratio of mean angular displacement of MCP, DIP, and PIP joints of “slave” finger to the average MCP joint displacement of “master” digit). The authors discovered that the individuation index was not significantly different between the passive and active conditions, suggesting that mechanical factors could have contributed more towards enslaving compared to neural factors. Mirakhorlo and colleagues (2017) recorded isometric force of “slave” fingers during a static phase (1 s of voluntary isometric index finger flexion at a constant force) and dynamic phase (~ 1.35 s of index MCP isotonic flexion at ~ 30 °/s; performed immediately after the static phase). The authors observed a significant increase in “slave” forces during the dynamic phase compared to the static phase. Furthermore, the time delay between the onset of index finger dynamic flexion and the rise in “slave” fingertip force ranged from 260 to 370 ms (note: index MCP was ~

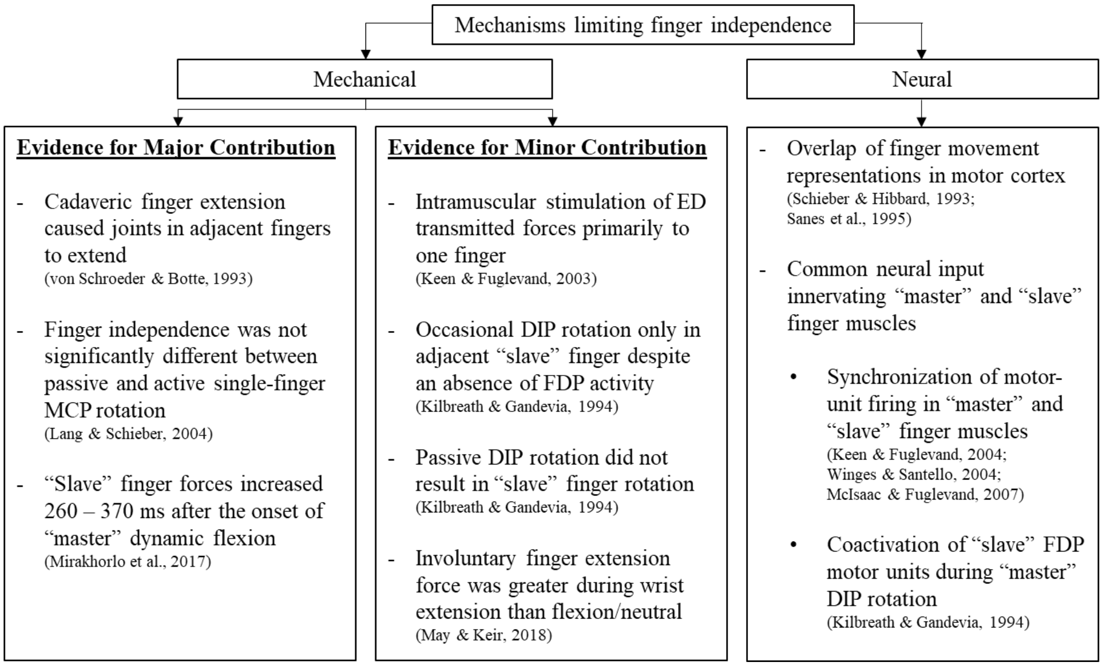
4° to 6° when “slave” forces started to increase). The authors attributed the delay to the time taken by the connective tissues between finger flexors to be pulled taut to enable force transmission between fingers, thus, indicating that mechanical factors could have played a major role in enslaving. May and Keir (2018) found higher involuntary forces and ED muscle activity during finger extensions performed with an extended wrist compared to flexed and neutral postures, which contradicted their hypothesis (note: MCP joints were straight). They expected higher involuntary forces in a flexed wrist due to the increased magnitude of passive force resulting from the stretched extensor tendons, transmitted via juncturae tendineii. Although their findings suggested a lower mechanical contribution, the juncturae tendineii in straight MCP posture might not have been completely stretched, limiting force transmission across fingers. Accordingly, the contribution of mechanical factors could be further assessed by flexing the MCP postures to allow greater strain of the passive connections, increasing the magnitude of forces transmitted between the tendons. Overall, the contrasting findings across these studies warrant further investigation into the contribution of passive intertendinous structures and deepen our understanding of the mechanisms that limit finger independence.

2.2.2 Neural Factors

Overlap of finger movement representations in the primary motor cortex (M1) has been suggested as one of the neural factors of enslaving. Schieber and Hibbard (1993) analyzed the spatial distribution of neuronal activity for the hand region in M1 of a rhesus monkey, during single-finger flexion-extension performed using each digit. They found that most neurons throughout the M1 hand region were activated (at different firing rates) during each “master” finger movement, suggesting an overlap of cortical territories representing the movements of different digits. Using functional magnetic resonance imaging in humans, Sanes et al. (1995) discovered substantial overlap of the activated M1 regions during flexion-extension tasks performed separately by the index and ring fingers, further supporting the findings of Schieber and Hibbard (1993).

During isometric finger contractions, synchronous firing of motor units was observed in “master” and “slave” ED (Keen & Fuglevand, 2004), FDP (Winges & Santello, 2004), and FDS (McIsaac & Fuglevand, 2007). Motor-unit synchrony across the different muscles may indicate the presence of a common neural input to motor neurons innervating the finger extensors, resulting in simultaneous finger force production. The motor-unit synchrony between the ring finger and the adjacent digits (middle or little) is greater in ED compared to FDS or FDP (Keen & Fuglevand, 2004; Winges & Santello, 2004; McIsaac & Fuglevand, 2007). This evidence could explain the findings of Sanei & Keir (2013), who showed that the ring finger was less independent (i.e. produced greater involuntary forces) during extension than flexion.

Using intramuscular electrodes, Kilbreath and Gandevia (1994) found activation of the “slave” FDP during “master” DIP joint movement, which further supports the theory of a neural input that diverges to motor neurons activating the “master” and “slave” finger muscles. At a given “master” finger force level, Sanei and Keir (2013) observed greater activation in adjacent “slave” FDS compared to non-adjacent “slave” FDS. This may indicate that the neural input to the “master” finger could have diverged and innervated the adjacent “slave” fingers, then gradually activated the non-adjacent “slave” fingers (Kilbreath & Gandevia, 1994). Involuntary activation of “slave” finger muscles increases with “master” finger force level (Sanei & Keir, 2013), suggesting that increased neural drive to the “master” finger could strengthen the neural input to the motor neurons innervating the “slave” fingers. A summary of the mechanical and neural mechanisms of enslaving has been summarized in Figure 2.4.



Evidence for Major Contribution

- Cadaveric finger extension caused joints in adjacent fingers to extend (von Schroeder & Botte, 1993)
- Finger independence was not significantly different between passive and active single-finger MCP rotation (Lang & Schieber, 2004)
- “Slave” finger forces increased 260 – 370 ms after the onset of “master” dynamic flexion (Mirakhorlo et al., 2017)

Evidence for Minor Contribution

- Intramuscular stimulation of ED transmitted forces primarily to one finger (Keen & Fuglevand, 2003)
- Occasional DIP rotation only in adjacent “slave” finger despite an absence of FDP activity (Kilbreath & Gandevia, 1994)
- Passive DIP rotation did not result in “slave” finger rotation (Kilbreath & Gandevia, 1994)
- Involuntary finger extension force was greater during wrist extension than flexion/neutral (May & Keir, 2018)

- Overlap of finger movement representations in motor cortex (Schieber & Hibbard, 1993; Sanes et al., 1995)
- Common neural input innervating “master” and “slave” finger muscles
  - Synchronization of motor-unit firing in “master” and “slave” finger muscles (Keen & Fuglevand, 2004; Winges & Santello, 2004; McIsaac & Fuglevand, 2007)
  - Coactivation of “slave” FDP motor units during “master” DIP rotation (Kilbreath & Gandevia, 1994)

Figure 2.4: Summary of the mechanisms (mechanical and neural factors) that limit finger independence. The figure also depicts the inconsistent evidence regarding the contribution of passive structures (mechanical factors) towards enslaving (production of involuntary finger force or movement).

2.3 Proposed Approach for Quantifying Mechanical Contribution

In this thesis, a simplified approach was proposed for quantifying the contribution of juncturae tendineii towards enslaving in different wrist and finger postures. Voluntary “master” finger extension causes the “slave” fingers to produce involuntary force and ED activity. Involuntary force is due to: (a) forces transmitted via juncturae tendineii, and (b) forces resulting from the involuntary activation of “slave” ED. Involuntary activation of ED is due to a common neural input innervating the “master” and “slave” ED (Keen and Fuglevand, 2004).

Surface electromyography (EMG) amplitude is often used as an estimate of neural input magnitude (Farina et al., 2010). If a “slave” finger were to voluntarily extend at an EMG amplitude equivalent to its involuntary activation level, we assumed that the equivalent extensor activity would maintain consistent neural input to the muscle, thus, produce comparable force. This essentially assumed that the voluntary force would be comparable to the involuntary force attributed to the neural factors of enslaving.

During voluntary finger extension, we assumed that juncturae tendineii would not contribute to voluntary force in the “intended” finger. The assumption was based on a simplified representation of the juncturae tendineii (Figure 2.5). We assumed that the “master” (e.g. ring) extensor tendon pulls on the juncturae tendineii, and not vice versa, as a result of voluntary muscle contraction of the “master” finger (Figure 2.5). The forces transferred through the intertendinous connections would then pull on the “slave” (e.g. middle) extensor tendon, producing involuntary force. Based on this theoretical framework, the difference between the involuntary and voluntary middle finger force could be attributed to mechanical factors of enslaving.

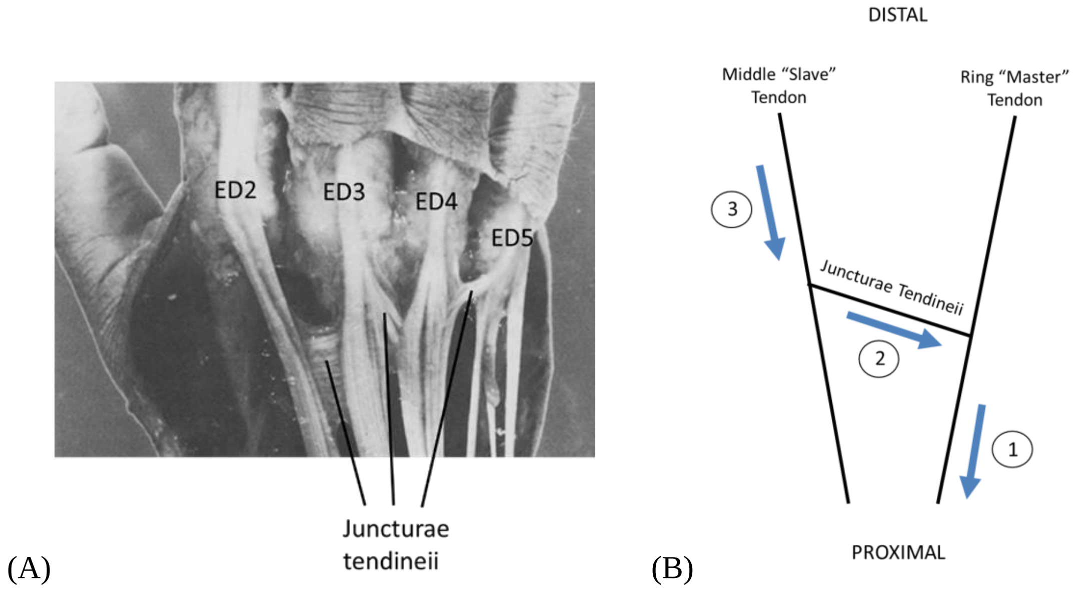


Figure 2.5: (A) Dorsal view of a cadaveric hand, depicting the juncturae tendineii between the ED tendons (von Schroeder et al., 1990). ED2-5 refers to the extensor digitorum tendons of index, middle, ring, and little fingers respectively. (B) Simplified representation of the juncturae tendineii between the "master" (e.g. ring) and "slave" (e.g. middle) extensor tendons. The arrows with numbers denote the mechanism of enslaving resulting from mechanical factors: (1) Voluntary contraction of ring extensor muscle pulls the ring finger tendon; (2) Juncturae tendineii are pulled by the ring extensor tendon; (3) Middle extensor tendon is pulled by the forces transmitted via juncturae tendineii, producing involuntary finger force.

Based on the proposed technique, hypothetical mechanical contribution is determined using involuntary and voluntary forces at a given finger extensor EMG amplitude, as shown in the equation below:

$$Hypothetical\ Mechanical\ Contribution\ (\%) = \frac{Involuntary\ Force\ -\ Voluntary\ Force}{Involuntary\ Force}\ x\ 100\%$$

For example, assume a task in which the ring “master” finger voluntarily extended at 15 N (isometric force), causing the middle “slave” finger to involuntarily extend at 5 N (isometric force), and generating an activation level of 10% maximum voluntary excitation (MVE) in the middle finger extensor muscle. In a separate isometric task, assume the middle finger voluntarily extended at 10% MVE and produced only 3 N of extension force. Mechanical contribution to the middle finger can therefore be determined by expressing the difference between involuntary and voluntary force (2 N) relative to the involuntary force (5 N) and multiplying the result by 100%. Based on the scenario above, the mechanical contribution to the middle finger would be 40%.

2.4 Summary

Finger control is essential for performing daily living and occupational tasks. An individual's ability in performing these tasks could be affected by limited finger independence, which is attributed to both mechanical and neural factors. The contribution of passive intertendinous structures (i.e. mechanical factors) towards involuntary finger force production remains unclear. By quantifying the mechanical contribution to enslaving, we can broaden our understanding of the mechanisms that limit finger independence, and this may help us develop better strategies for improving finger control and rehabilitation.

2.5 Purpose

The objective of this thesis was to quantify the mechanical contribution of juncturae tendineii in different wrist and MCP postures using a novel experimental paradigm. We also evaluated the effects of wrist and MCP posture on finger force and extensor EMG amplitude during submaximal finger extensions.

2.6 Hypothesis

It was hypothesized that the mechanical contribution could be determined by analyzing the voluntary and involuntary finger extension forces at a given ED activation level. Additionally, the hypothetical mechanical contribution was hypothesized to be within the range of 0 to 100%.

CHAPTER 3: MANUSCRIPT

Quantifying the Contribution of Passive Structures in Finger Independence

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3.1 Abstract

Mechanical and neural factors have been suggested to limit finger independence. Fingers producing involuntary movement or force production during intended actions of another finger are considered “enslaved” to that finger. The purpose of this thesis was to quantify the contribution of passive mechanical factors to this enslaving effect, in particular, the contributions of the intertendinous connections between extensor tendons. Twenty participants (10 men, 10 women) performed *Master* and *Slave Tasks* in three wrist (30° extension, neutral, 30° flexion) and two metacarpophalangeal (MCP) (straight and 90° flexion) postures. During the *Master Task,* the ring finger was the intended or “master” finger. Three 10 s isometric ring finger extensions were performed at 25% of maximum voluntary contraction. Finger force and surface electromyography of the 4 extensor digitorum (ED) bellies were recorded. In the *Slave Tasks,* the middle and little fingers (“slave” fingers during the *Master Task*) each performed three 10 s isometric finger extensions at their mean activation levels during the *Master Task.* Hypothetical mechanical contribution (HMC) was determined for the middle and little fingers. The HMC was defined as the difference between the involuntary force (from the *Master Task*) and the voluntary force (from the *Slave Task*) relative to the involuntary force. A small proportion of the HMC values (Middle: 39%; Little: 15%) were within the expected range of 0 to 100%, suggesting that the equation developed in this study provided a limited representation of the contribution of passive intertendinous structures. Index finger forces increased with MCP flexion, suggesting the importance of juncturae tendineii in finger independence. Higher ED activity during wrist extension, than neutral or flexed postures,

with straight MCP supports previous evidence in the literature. The complex phenomenon of enslaving in different wrist and MCP positions warrants further research for quantifying the mechanical contribution in finger independence.

3.2 Introduction

Finger control is important for performing activities of daily living including occupational tasks such as writing, typing, and handling tools. However, fingers do not act completely independently. Movement or force generation of any given finger causes other digits to move or produce force involuntarily (Zatsiorsky et al., 2000; Sanei & Keir, 2013; van den Noort et al., 2016; Mirakhorlo et al., 2017; van Beek et al., 2018; May & Keir, 2018; Mirakhorlo et al., 2018). The phenomenon of involuntary movement or force production is known as "enslaving" (Zatsiorsky et al., 2000). The finger intended to move or produce force is referred to as the "master" or "intended" finger, whereas the fingers generating involuntary movement or force are known as "slave" or "non-intended" fingers. A lack of finger independence may affect an individual's dexterity and task performance. For example, enslaving during typing may cause an individual to press an incorrect key unintentionally, hence, reducing accuracy. Therefore, a deeper understanding of the mechanisms that limit finger independence is crucial for creating strategies to improve finger control and rehabilitation.

The lack of finger independence has been attributed to mechanical and neural factors but rarely delineated between them. Mechanically, enslaving results from forces transmitted through juncturae tendineii (passive intertendinous connections) between the extensor digitorum (ED) tendons (von Schroeder & Botte, 1993). Similarly, connective tissues between tendons and muscle bellies of flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) transfer force across fingers, producing involuntary forces (Leijnse et al., 1997). Neurally, the overlap of finger movement representations in the primary motor cortex have been suggested to generate involuntary finger movement (Schieber and Hibbard, 1993). Synchronous firing of motor units in the muscle bellies of ED (Keen & Fuglevand, 2004), FDP (Winges & Santello, 2004), and FDS (McIsaac & Fuglevand, 2007) may also explain the involuntary force production.

Contribution of passive intertendinous connections towards enslaving remains unclear. Juncturae tendineii (passive connections between ED tendons) have been shown to have a minor role in distributing forces across fingers during intramuscular stimulation of ED (Keen & Fuglevand, 2003). Conversely, Lang and Schieber (2004) found that the magnitude of “slave” finger joint movement was similar during passive and active flexion-extension of the “master” metacarpophalangeal (MCP) joint, suggesting that mechanical factors (intertendinous connections) could be a primary contributor to enslaving. May and Keir (2018) discovered greater involuntary forces and ED activity during finger extensions performed with an extended wrist than flexed and neutral postures. This result contradicted their hypothesis because they predicted greater involuntary forces in a flexed wrist due to the increased magnitude of passive forces resulting from the stretched extensor tendons, transferred via juncturae tendineii. Although the finding from May and Keir (2018) suggested a lower contribution of juncturae tendineii, it is important to note that they kept the MCP joints straight. The juncturae tendineii in that finger posture might not have been stretched, limiting force transmission across fingers. Therefore, the contribution of the intertendinous structures could be further assessed by flexing the MCP postures to increase strain of the passive connections, enabling greater force transmission across tendons. Overall, conflicting findings across these studies warrant further investigation into the contribution of mechanical factors and broaden our understanding of the mechanisms that limit finger independence.

In this paper, we proposed a simplified approach for deducing the contribution of juncturae tendineii towards enslaving in different wrist and MCP postures. Voluntary “master” finger extension causes the “slave” fingers to produce involuntary force and ED activity. Involuntary force is due to: (a) forces transmitted via juncturae tendineii, and (b) forces resulting from the involuntary activation of “slave” ED. Involuntary activation of ED is due to a common neural input innervating the “master” and “slave” ED (Keen and Fuglevand, 2004).

Surface electromyography (EMG) amplitude is often used as an estimate of neural input magnitude (Farina et al., 2010). If a “slave” finger were to voluntarily extend at an EMG amplitude equivalent to its involuntary activation level, we assumed that the equivalent extensor activity would maintain consistent neural input to the muscle, thus, produce comparable force. This essentially assumed that the voluntary force would be comparable to the involuntary force attributed to the neural factors of enslaving.

During voluntary finger extension, we assumed that juncturae tendineii would not contribute to voluntary force in the “intended” finger. The assumption was based on a simplified representation of the juncturae tendineii (Figure 3.1). We assumed that the “master” (e.g. ring) extensor tendon pulls on the juncturae tendineii, and not vice versa, as a result of voluntary muscle contraction of the “master” finger (Figure 3.1). The forces transferred through the intertendinous connections would then pull on the “slave” (e.g.

middle) extensor tendon, producing involuntary force. Based on this theoretical framework, the difference between the involuntary and voluntary middle finger force could be attributed to mechanical factors of enslaving.

The purpose of this paper was to quantify the contribution of passive intertendinous structures in different wrist and MCP postures using a novel experimental paradigm. We also evaluated the effects of wrist and MCP posture on finger force and ED activation level during submaximal finger extensions. We hypothesized that the mechanical contribution could be determined by evaluating voluntary and involuntary finger extension forces at a given ED activity level.

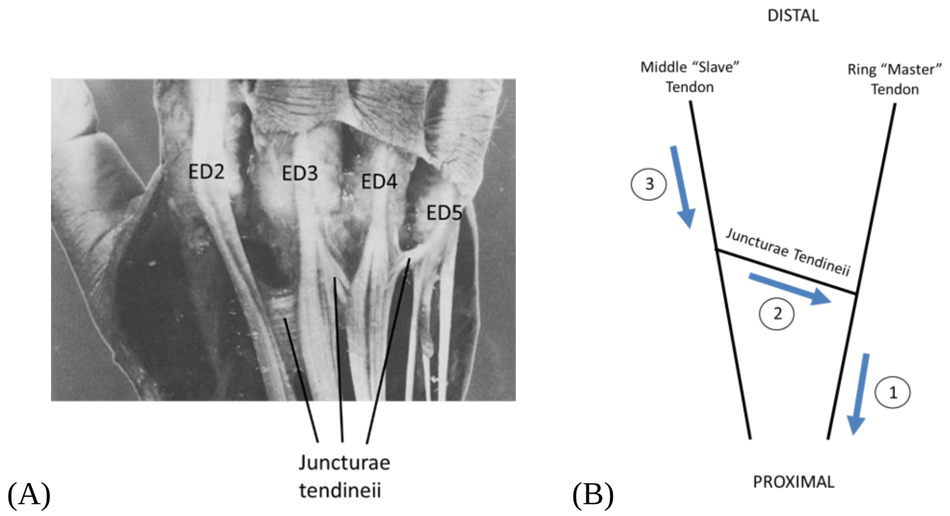


Figure 3.1: (A) Dorsal view of a cadaveric hand, depicting the juncturae tendineii between the ED tendons (von Schroeder et al., 1990). ED2-5 refers to the extensor digitorum tendons of index, middle, ring, and little fingers respectively. (B) Simplified representation of the juncturae tendineii between the "master" (e.g. ring) and "slave" (e.g. middle) extensor tendons. The arrows with numbers denote the mechanism of enslaving resulting from mechanical factors: (1) Voluntary contraction of ring extensor muscle pulls the ring finger tendon; (2) Juncturae tendineii are pulled by the ring extensor tendon; (3) Middle extensor tendon is pulled by the forces transmitted via juncturae tendineii, producing involuntary finger force.

3.3 Methods

3.3.1 Participants

Twenty right-handed participants from the McMaster University student population were recruited (10 men and 10 women). Participants were 24.9 ± 2.2 years old (mean ± standard deviation), 74.0 ± 14.3 kg, and 172.8 ± 11.7 cm in height. Their forearm and hand lengths were 25.6 ± 2.3 cm and 18.5 ± 1.3 cm, respectively. Participants were screened to exclude individuals with history of upper extremity musculoskeletal disorders. The study protocol was approved by the McMaster Research Ethics Board. Participants provided informed written consent.

3.3.2 Experimental Set-up and Instrumentation

Participants were seated upright with the right wrist and elbow placed on a padded support while maintaining a mid-prone forearm position (Figure 3.2). An adjustable metal ring was placed around the proximal phalanx of digits 2-5 (index, middle, ring, and little fingers). Each ring was attached to a uniaxial force transducer (MLP50, Transducer Techniques, CA, USA) affixed to a metal plate that was firmly secured to the table (Figure 3.2). The setup was adjusted to accommodate three wrist postures (30° flexion, neutral, 30° extension) and two MCP postures (0° and 90° flexion of digits 2-5) (Figure 3.3).

Figure 3.2: Experimental set-up depicting the finger and hand positioning within the testing apparatus. Fingers were placed in adjustable metal rings (circled in white), each secured to a force transducer and attached to a metal plate. The wrist and elbow were supported using pads to maintain a mid-prone forearm position.

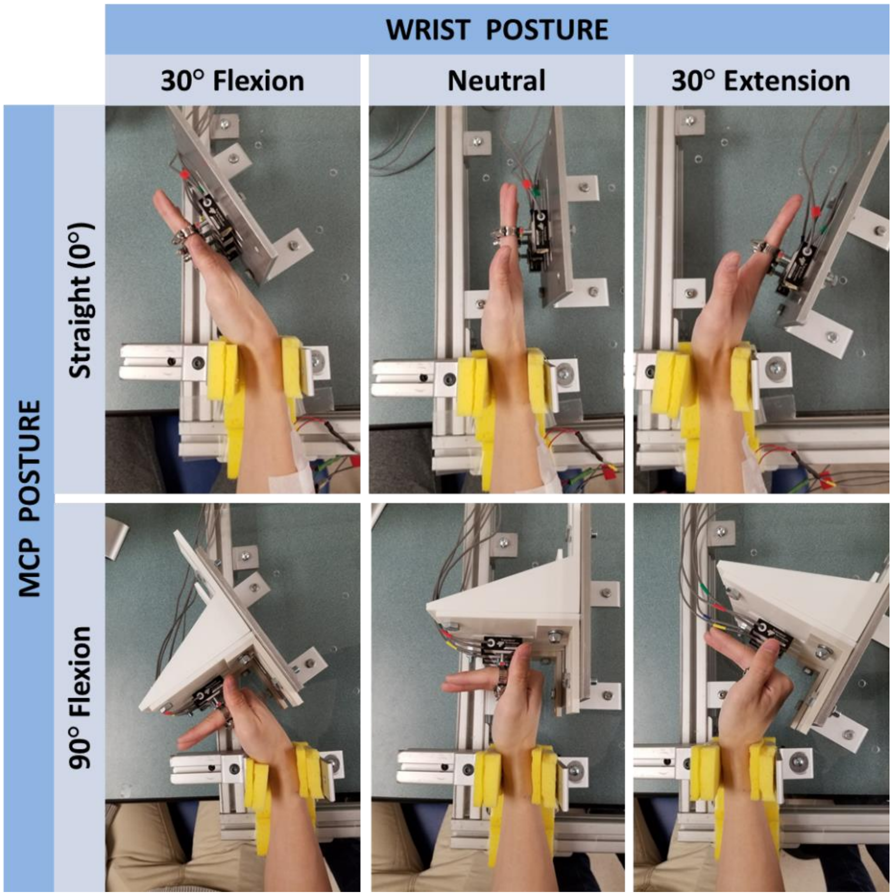


Figure 3.3: Experimental set-up in all wrist (30° flexion, neutral, and 30° extension) and MCP (straight and 90° flexion) posture combinations.

Muscle activity of the extensor digitorum (ED) was recorded using bipolar surface electrodes with a fixed interelectrode distance of 2 cm (SEMG/NCV, Natus Neurology Inc., ON, CA). For each belly of ED, electrode sites on the skin were shaved and scrubbed with isopropyl alcohol before placing the electrodes over the muscle belly parallel to the fibre direction. Electrode locations were based on literature (Leijnse et al., 2008; May & Keir, 2018) (Figure 3.4) and confirmed using manual palpation. A summary of electrode locations is included in Table 3.1. The muscle belly of ED5 was not consistently distinguishable from extensor digitorum minimi, thus, the pair of electrodes might have recorded the combined activity of both muscles (Leijnse et al., 2008; Sanei & Keir, 2013; May & Keir, 2018).

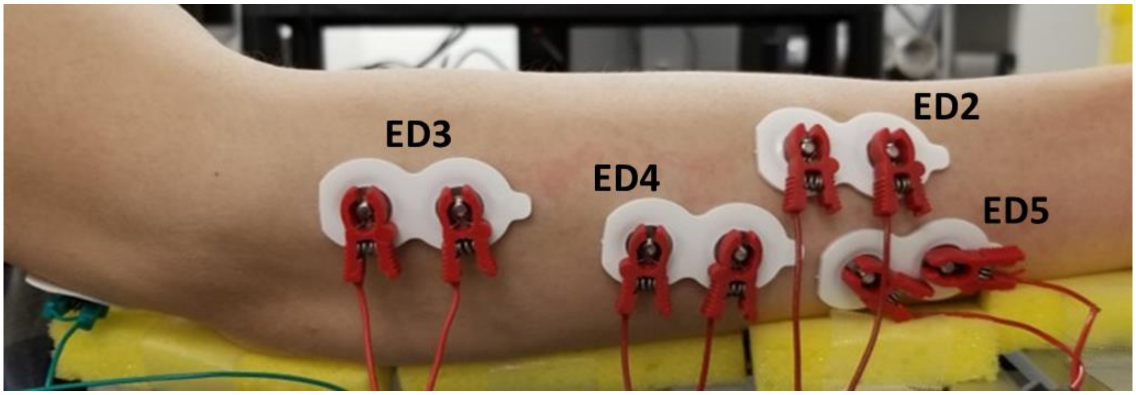


Figure 3.4: Electrode placement locations for ED. ED2-5 represents the electrodes used for recording the activity of index, middle, ring, and little finger extensors, respectively.

Table 3.1: Electrode locations of ED2-5 (Leijnse et al., 2008; May & Keir, 2018).

Muscle	Electrode Location
ED2	Halfway along the forearm, at the medial border of ED
ED3	Distal to the humeroradial joint, at ED midline
ED4	Parallel to ED2 electrodes, distal to ED3 electrodes, at the ulnar border
ED5	Halfway along the forearm (or more distal if required based on palpation of muscle belly), distal to ED4 electrodes

EMG signals were differentially amplified (CMRR > 115 dB, input impedance ~ 10 GΩ) and bandpass filtered (10-1000 Hz) (AMT-8, Bortec Biomedical Ltd., AB, CA) prior to synchronously sampling with force at 2000 Hz (16 bit, USB-6229, National Instruments, TX, USA) and collected using a custom program (LabView 2017, National Instruments, TX, USA). Raw force and EMG data were processed using a custom MATLAB program (Version 9.4, MathWorks, Natick, MA, USA).

3.3.3 Experimental Protocol

The experimental protocol involved isometric finger extensions performed in three wrist postures (30° flexion, neutral, and 30° extension) using two MCP postures (straight and 90° flexion of digits 2-5). A 10 s quiet trial was collected with the right forearm in a mid-prone position on the padded support of the experimental setup. Mean of the middle 6 s of the quiet trial was used to debias force and EMG signals. Participants performed two 5 s maximal voluntary isometric extensions with each finger in neutral wrist with straight MCP posture. Debiased forces were low pass filtered using a single-pass critically damped filter (f_c = 10 Hz). The highest peak filtered force across the trials was used as 100% maximum voluntary contraction (MVC) for a given finger. Force of each finger was normalized to the MVC of corresponding digits. Debiased EMG signals were full-wave rectified, and low pass filtered using a single-pass critically damped filter (f_c = 3 Hz). The highest peak in the filtered EMG data collected during the trials was used as 100% maximum voluntary excitation (MVE) for a given muscle. EMG of each muscle was normalized to the MVE of respective muscles.

The wrist and MCP joints were then moved to one of the 6 posture combinations (Figure 3.3). A 10 s resting trial was collected in each posture to record the resting forces exerted by each finger. During this trial, participants were instructed to relax and not actively exert any force against the rings. Participants then completed a *Master Task* using the ring finger, followed by a *Slave Task* for each of the middle and little fingers.

In the *Master Task,* participants performed three 10 s isometric ring “master” finger extensions. Each trial was separated by 10 s rest. Participants were instructed to maintain the ring finger force within 0.5% MVC of target force level (25% MVC). Force and EMG of digits 2-5 were recorded. A 1 second moving average of ring “master” finger force was calculated for each trial. For analysis, a 1 second window within ± 0.5% MVC of the target force level (25% MVC) with the lowest standard deviation was selected for each trial. Force and EMG were averaged across the three windows for each finger. In this task, the ring finger was the “master” finger, whereas the other fingers were referred to as “slave” fingers.

In the *Slave Tasks*, participants performed three 10 s isometric extensions using the middle and little fingers (separately). Each trial was separated by 10 s rest.

Participants were instructed to maintain the intended finger (middle or little) EMG within 0.5% MVE of the target EMG level. The target EMG level for the intended finger was equivalent to the mean EMG amplitude produced by the digit in the *Master Task*. Force and EMG of digits 2-5 were recorded. A 1 second moving average of intended finger (middle or little) EMG was calculated in each trial. For analysis, a 1 second window within ± 0.5% MVE of the target EMG level with the lowest standard deviation was selected for each trial. Force and EMG were averaged across the three windows for each finger. The middle and little fingers were the "intended" fingers for the respective *Slave Tasks*, whereas the other fingers were known as "non-intended" fingers.

Visual feedback of normalized force (during the *Master Task*) and EMG level (during the *Slave Task*) were provided for participants to maintain the required target levels (LabView 2017, National Instruments, TX, USA). Visual feedback also included upper and lower bounds of 0.5% MVC within target force level (*Master Task*) and 0.5% MVE within target EMG amplitude (*Slave Task*). After completing the *Master* and *Slave Tasks*, participants then performed two 5 s maximal extensions in each finger, before advancing to the next posture. The order of MCP and wrist positions were randomized. Participants completed the trials for each wrist posture within one MCP posture before performing the tasks in the other MCP position. A flowchart of the experimental protocol has been illustrated in Figure 3.5.

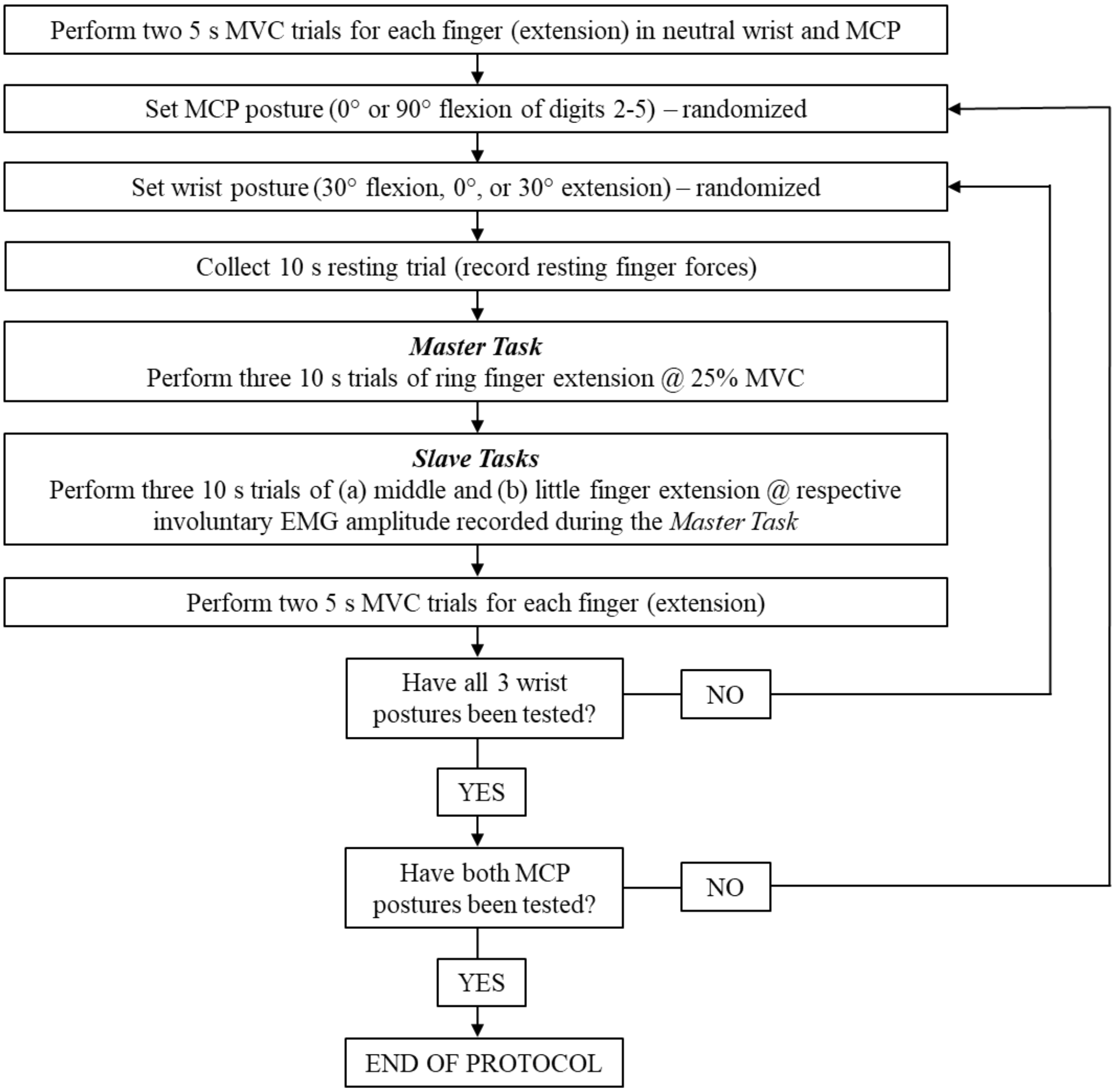


Figure 3.5: Flowchart illustrating the experimental protocol.

3.3.4 Data Analysis

To quantify the hypothetical mechanical contribution (HMC) of the passive force (assumed to be from the juncturae tendineii) towards enslaving, the following equation was used for each of the middle and little fingers (Equation 1):

$$Hypothetical\ Mechanical\ Contribution\ (\%) = \frac{Involuntary\ Force - Voluntary\ Force}{Involuntary\ Force}\ x\ 100\% \qquad (1)$$

where, involuntary and voluntary forces of a finger were obtained from the *Master* and *Slave Tasks*, respectively. Based on this equation, involuntary force was assumed to include the forces resulting from mechanical and neural factors of enslaving. Voluntary force was assumed to be equivalent to the magnitude of involuntary force attributed to the neural factors of enslaving. For example, if the middle finger produced 5 N of involuntary force during the *Master Task* and 3 N of voluntary force in the *Slave Task* (intended finger = middle), then HMC for the middle digit would be 40%. Based on *Equation 1*, we hypothesized that HMC would be between 0 and 100% for the middle and little fingers in each of the wrist and MCP posture combinations. Data analysis was performed for only 19 participants because one of the force transducers malfunctioned for one participant.

3.3.5 Statistical Analysis

Means and standard deviations were calculated for outcome measures (HMC, force, and EMG) for all postures. A 3 (wrist posture) x 2 (MCP posture) repeated measures ANOVA was conducted to evaluate the effects of wrist and MCP posture on force and EMG, separately for each finger during the *Master* and *Slave Tasks*. The Greenhouse-Geisser correction was applied to the degrees of freedom of the F-statistic to correct for sphericity violation. Normality was tested using Shapiro-Wilk test and visually confirmed using normal quantile-quantile plots. Significant effects were analyzed post-hoc using t-tests with Holm-Bonferroni correction. Effect sizes were calculated using generalized eta squared (η_G^2). Statistical tests were conducted in RStudio (v1.1.419, RStudio Inc., MA, USA) with $\alpha = 0.05$.

3.4 Results

3.4.1 Maximum and Resting Forces

Maximum voluntary extension force as well as resting force of digits 2-5 for each wrist and MCP posture are summarized in Tables 3.2 and 3.3, respectively.

Table 3.2. Maximum finger force (in N, mean ± standard deviation) for all fingers in each of the six wrist and MCP posture combinations. Maximum forces recorded during neutral wrist with straight MCP (shaded in grey) were used as MVCs.

Wrist Posture	MCP Posture	Index	Middle	Ring	Little
30° Extension	Straight (0°)	19.3 ± 5.8	14.1 ± 3.7	9.0 ± 2.2	11.2 ± 2.9
	90° Flexion	24.3 ± 9.9	16.2 ± 4.6	8.5 ± 2.3	11.3 ± 4.4
Neutral	Straight (0°)	21.9 ± 7.0	14.9 ± 3.2	11.3 ± 2.0	12.9 ± 3.8
	90° Flexion	23.1 ± 4.8	14.9 ± 3.8	8.8 ± 2.5	10.2 ± 3.4
30° Flexion	Straight (0°)	21.8 ± 4.7	15.1 ± 3.2	11.5 ± 3.0	12.0 ± 4.0
	90° Flexion	22.2 ± 5.8	15.4 ± 3.5	8.6 ± 2.1	9.5 ± 3.5

Table 3.3. Resting finger force (in N, mean ± standard deviation) in each of the six wrist and MCP posture combinations. Positive and negative values indicate forces in extension and flexion directions, respectively.

Wrist Posture	MCP Posture	Index	Middle	Ring	Little
30° Extension	Straight (0°)	2.1 ± 0.5	0.7 ± 0.4	-0.5 ± 0.6	0.5 ± 0.4
	90° Flexion	3.1 ± 0.4	1.4 ± 0.4	-0.4 ± 0.6	0.5 ± 0.8
Neutral	Straight (0°)	2.2 ± 0.4	1.1 ± 0.6	-0.4 ± 0.4	0.8 ± 0.3
	90° Flexion	3.7 ± 0.5	1.7 ± 0.4	-0.1 ± 0.4	0.7 ± 0.7
30° Flexion	Straight (0°)	2.8 ± 0.6	1.7 ± 0.7	-0.1 ± 0.5	0.8 ± 0.4
	90° Flexion	4.4 ± 0.6	2.0 ± 0.6	0.1 ± 0.4	0.8 ± 0.3

3.4.2 Hypothetical Mechanical Contribution

Hypothetical mechanical contribution (HMC) in each posture was determined by subtracting the voluntary force from the involuntary force at a given ED activation level and expressing the difference relative to involuntary force prior to multiplying the result by 100% (Equation 1). The difference between involuntary and voluntary forces in the middle and little fingers were primarily less than zero for each posture, indicating greater voluntary than involuntary forces (Figure 3.6).

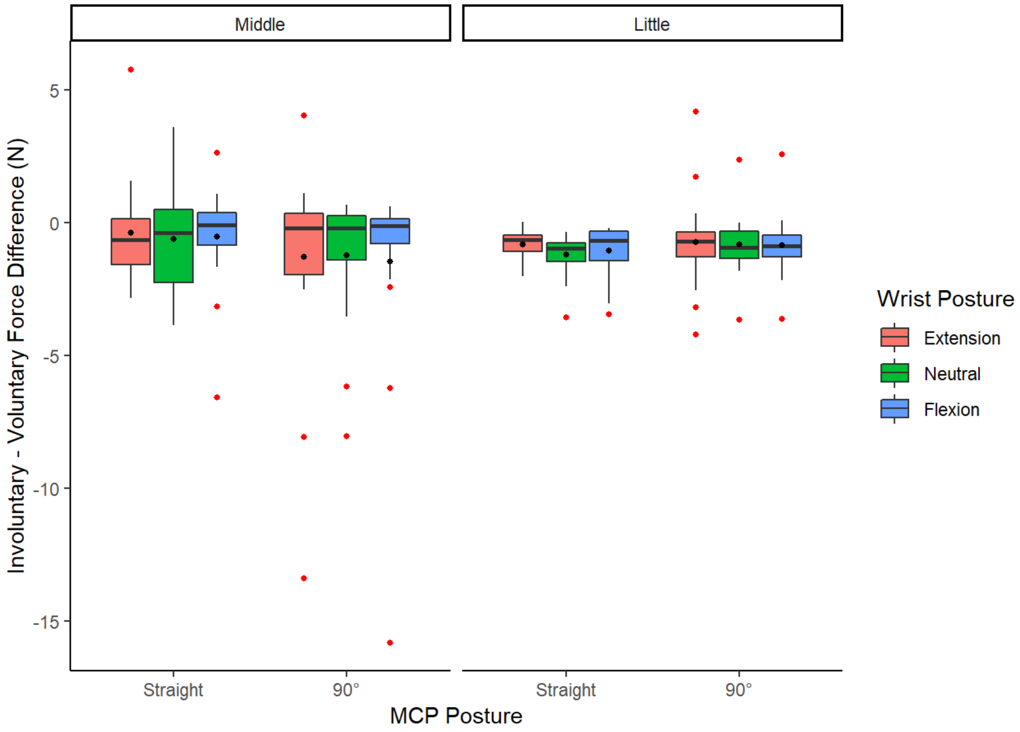


Figure 3.6: Boxplots of the difference between involuntary and voluntary force in middle and little fingers across the six wrist and MCP posture combinations. Means (black circles) and medians (thick horizontal lines) are presented. Coloured areas within the boxplots represent the interquartile range. Outliers are denoted with red dots. Note: Boxplots for HMCs are not presented due to its large range in scale. Individual HMCs are presented in Tables 3.4 & 3.5.

HMC for the middle and little fingers were primarily outside of the expected range of 0 to 100% (Tables 3.4 & 3.5). As there were 19 participants in each of the 6 wrist and MCP posture combinations, a total of 114 HMC values were determined for each of the two fingers. A small proportion (Middle: 39%; Little: 15%) of the data was within the expected range. Means ± standard deviation of HMC are presented in Table 3.6.

Table 3.4: HMC (%) in middle finger for each participant. Participant 16 was removed from analysis. HMCs within the expected range of 0 to 100% are shaded in grey.

Participant	Straight MCP			90° MCP Flexion		
	30° Wrist Extension	Neutral Wrist	30° Wrist Flexion	30° Wrist Extension	Neutral Wrist	30° Wrist Flexion
1	-105	-239	-15	-129	-65	-43
2	27	7	37	10	19	5
3	82	64	41	-3	-3	12
4	-132	516	-1081	-36	4	32
5	-29	-46	-1	-158	-77	-54
6	-78	5	1	-33	-23	-47
7	61	208	171	-35	45	26
8	-8	5	-27	11	12	-3
9	33	77	39	49	92	-83
10	-15	21	1	-7	-163	-728
11	-117	-199	-336	-218	-63	-43
12	-57	-217	-315	-53	-236	-492
13	27	16	-2	-37	-15	2
14	-101	-483	-58	8	-146	-10
15	38	34	35	22	9	10
17	-16	-117	-61	27	9	-40
18	10	599	-116	17	7	-3
19	-21896	-1010	-65	68	-17	-54
20	-16	-21	7	32	-17	-2

Table 3.5: HMC (%) in little finger for each participant. Participant 16 was removed from analysis. HMCs within the expected range of 0 to 100% are shaded in grey.

Participant	Straight MCP			90° MCP Flexion		
	30° Wrist Extension	Neutral Wrist	30° Wrist Flexion	30° Wrist Extension	Neutral Wrist	30° Wrist Flexion
1	-52	-93	-18	54	47	58
2	-61	-169	-102	37	99	-33491
3	-45	-32	-16	12	-36	-1
4	-34	-54	-26	-23	1	-13
5	-14	-12	-8	-31	-88	-1123
6	2	-118	-219	771	-138	-116
7	-21	-21	-34	-12	-140	-439
8	-428	-209	-249	-16	-53	-61
9	-42	-27	-180	-264	282	-92
10	-95	-94	-69	-327	0	-620
11	-46	-170	-22	-114	-158	-198
12	-11	-23	-20	745	-86	-326
13	-221	-1342	609	58	629	-27
14	56	68	74	31	29	51
15	-23	-378	-106	-3	-17	-131
17	-134	-219	-422	226	-130	597
18	-233	-249	-212	-69	-43	542
19	-442	-952	-2806	-1233	-39	133
20	-11	-49	-47	18	-4	-1

Table 3.6: Mean ± standard deviation of HMC (%) in the middle and little fingers in each of the wrist and MCP posture combination.

Finger	MCP Posture	Wrist Posture		
		30° Extension	Neutral	30° Flexion
Middle	Straight (0°)	-1173 ± 4546	-41 ± 733	-92 ± 994
	90° Flexion	-24 ± 980	-33 ± 958	-80 ± 975
Little	Straight (0°)	-98 ± 1404	-218 ± 1437	-204 ± 1509
	90° Flexion	-7 ± 1424	8 ± 1437	-1856 ± 7022

3.4.3 Force

There was a significant main effect of MCP posture on force for the index finger for *Master* and *Slave Tasks*. Force produced by the index finger was significantly greater in 90° MCP flexion than straight posture, regardless of wrist position (Figure 3.7 & 3.8). In the *Master Task*, mean force for the index "slave" finger across the three wrist postures was approximately 0.4% MVC during straight MCP and increased to nearly 12% MVC with 90° MCP flexion ($F_{(1, 18)} = 37.2$; $p < 0.001$; $n_G^2 = 0.27$). During the middle finger *Slave Task*, the mean index finger force across the wrist postures was nearly 4% MVC with a straight MCP and increased to approximately 15% MVC with MCP flexion ($F_{(1,18)} = 19.4$; $p < 0.001$; $n_G^2 = 0.10$) (Figure 3.8-A). During little finger *Slave Task*, mean index finger force across the wrist postures increased from nearly 0.5% MVC with straight MCP to approximately 9% MVC with 90° MCP flexion ($F_{(1, 18)} = 23.2$; $p < 0.001$; $n_G^2 = 0.26$) (Figure 3.8-B).

A significant wrist x MCP posture interaction on force for index finger was also detected during the little finger *Slave Task* ($F_{(1.5, 27.1)} = 18.8$; $p < 0.001$; $n_G^2 = 0.03$). Wrist extension (6.8 ± 8.9% MVC) resulted in lower force than neutral (8.6 ± 9.2% MVC) and flexed (12.7 ± 9.5% MVC) postures, only during 90° MCP flexion (Figure 3.8-B). Force was also significantly lower in neutral than flexed wrist posture, but only in 90° MCP flexion.

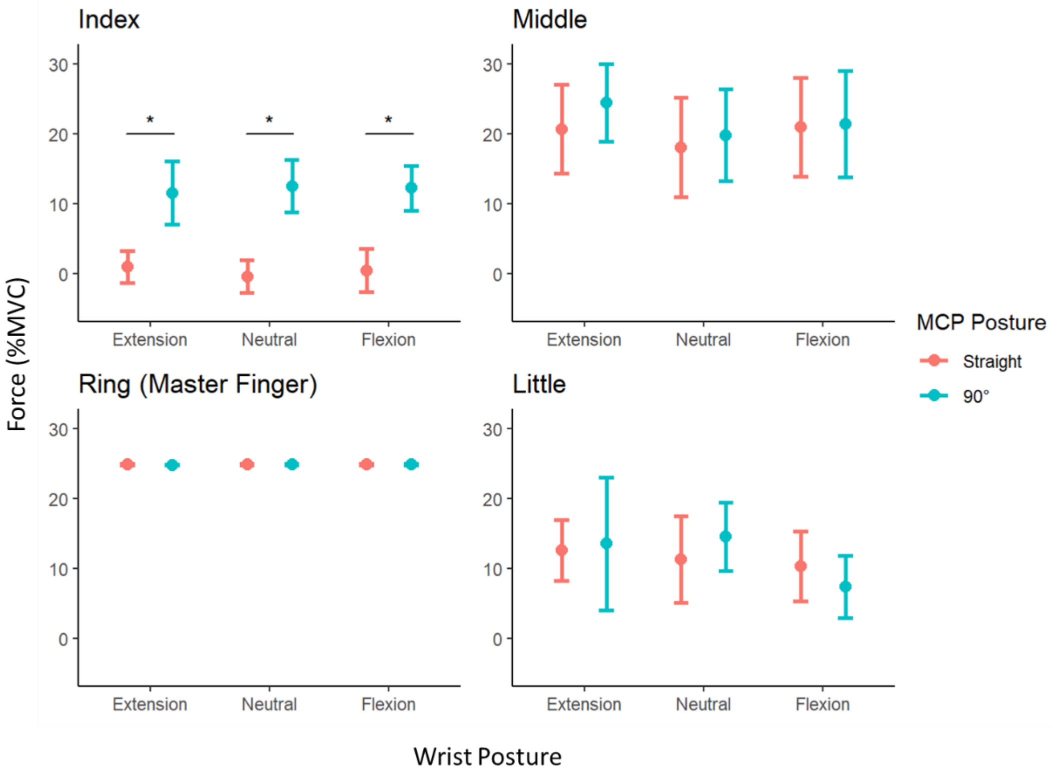
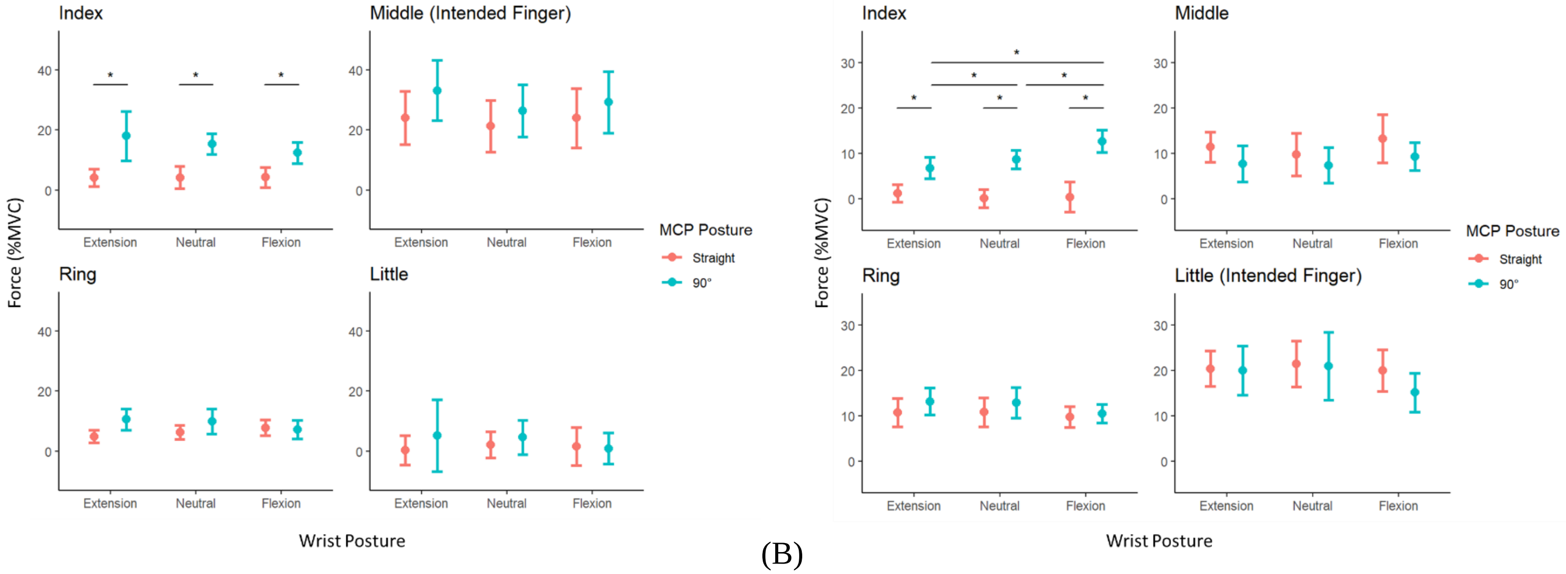


Figure 3.7: Effect of MCP posture on force during *Master Task*. Mean ± 95% confidence interval of force (% MVC) in index, middle, ring, and little fingers in each of the six wrist and MCP posture combinations are presented. Significant differences between postures are denoted with asterisks.



(A) (B)

Figure 3.8: Effect of MCP posture on force during (A) *Slave Task* (intended finger = middle) and (B) *Slave Task* (intended finger = little). Mean ± 95% confidence interval of force (% MVC) of index, middle, ring, and little fingers in each of the six wrist and MCP posture combinations are presented. Significant differences between postures are denoted with asterisks.

3.4.4 Muscle activity

In the *Master Task*, a significant wrist x MCP posture interaction on EMG was observed in the "master" ED4 (ring) and "slave" ED5 (little). "Master" ED4 activity was significantly greater in wrist extension (38.7 ± 14.2% MVE) than neutral posture (28.0 ± 12.9% MVE), only during straight MCP position ($F_{(1.9, 34.5)} = 6.1$; $p = 0.006$; $n_G^2 = 0.03$) (Figure 3.9). ED4 activity in a flexed wrist posture was significantly lower than in wrist extension, regardless of the MCP posture. "Slave" ED5 activity was significantly greater in wrist extension (32.1 ± 14.1% MVE) than neutral or flexed posture (22.5 ± 10.6% MVE and 18.0 ± 10.4% MVE, respectively), only during straight MCP ($F_{(1.9, 34)} = 6.1$; $p = 0.045$; $n_G^2 = 0.02$) (Figure 3.9). For "slave" ED3 (middle), there was a significant main effect of wrist posture on muscle activity ($F_{(1.5, 27)} = 19.0$; $p < 0.001$; $n_G^2 = 0.02$). "Slave" ED3 activity was significantly higher during wrist extension than neutral or flexed posture, regardless of MCP position (Figure 3.9).

During the middle finger *Slave Task*, there was a significant main effect of wrist posture on ED3 ($F_{(1.7, 29.8)} = 22.0$; $p < 0.001$; $n_G^2 = 0.02$), ED4 ($F_{(1.4, 24.4)} = 14.1$; $p < 0.001$; $n_G^2 = 0.06$), and ED5 activity ($F_{(1.7, 30.3)} = 5.0$; $p = 0.017$; $n_G^2 = 0.03$). Wrist extension elicited significantly greater activity in ED3 (intended finger), ED4, and ED5 than neutral and flexed postures, regardless of MCP position (Figure 3.10-A). ED4 activity was also significantly higher during neutral than flexed wrist, regardless of MCP posture.

During little finger *Slave Task*, there was a significant main effect of wrist posture on ED3 activity ($F_{(1.5, 26.4)} = 4.5$; $p = 0.03$; $n_G^2 = 0.01$). ED3 activity was significantly greater with wrist extension than neutral posture, regardless of MCP position (Figure

3.10-B). Additionally, there was a significant wrist x MCP posture interaction for ED4 ($F_{(2.0, 35.6)} = 18.8$; $p = 0.01$; $n_G^2 = 0.02$) and ED5 activity ($F_{(1.9, 34.4)} = 3.6$; $p = 0.041$; $n_G^2 = 0.02$) (Figure 3.10-B). Wrist extension produced significantly higher activity in ED4 and ED5 (intended finger) than neutral and flexed postures, only during straight MCP.

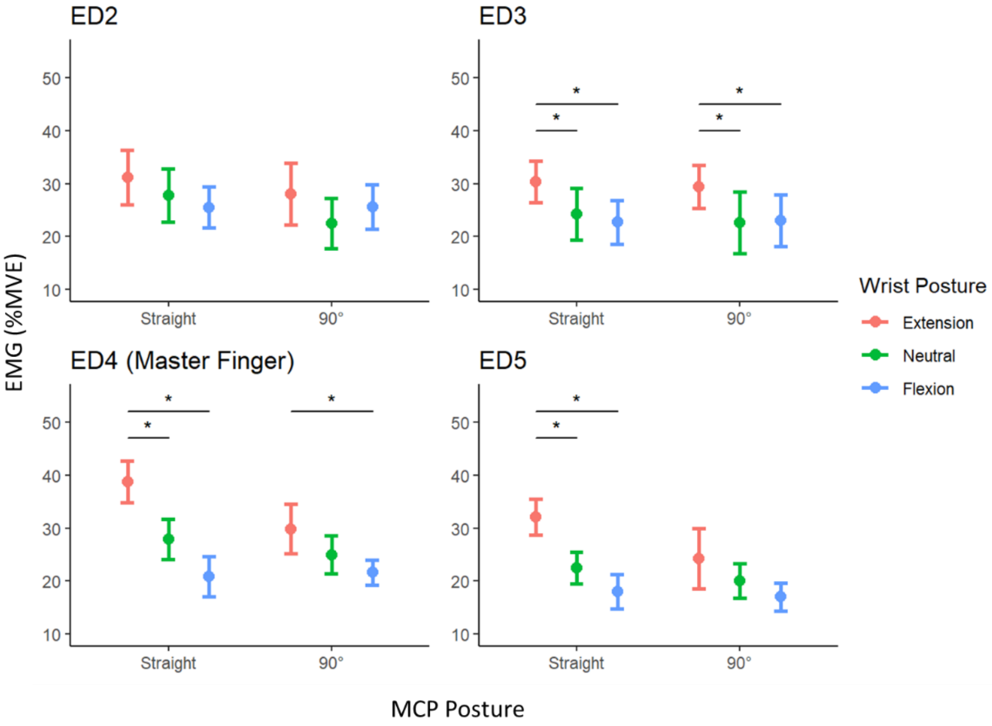


Figure 3.9: Effect of wrist posture on EMG during *Master Task*. Mean ± 95% confidence interval of EMG (% MVE) of ED2-5 in each of the six wrist and MCP posture combinations are presented. Significant differences between postures are denoted with asterisks.

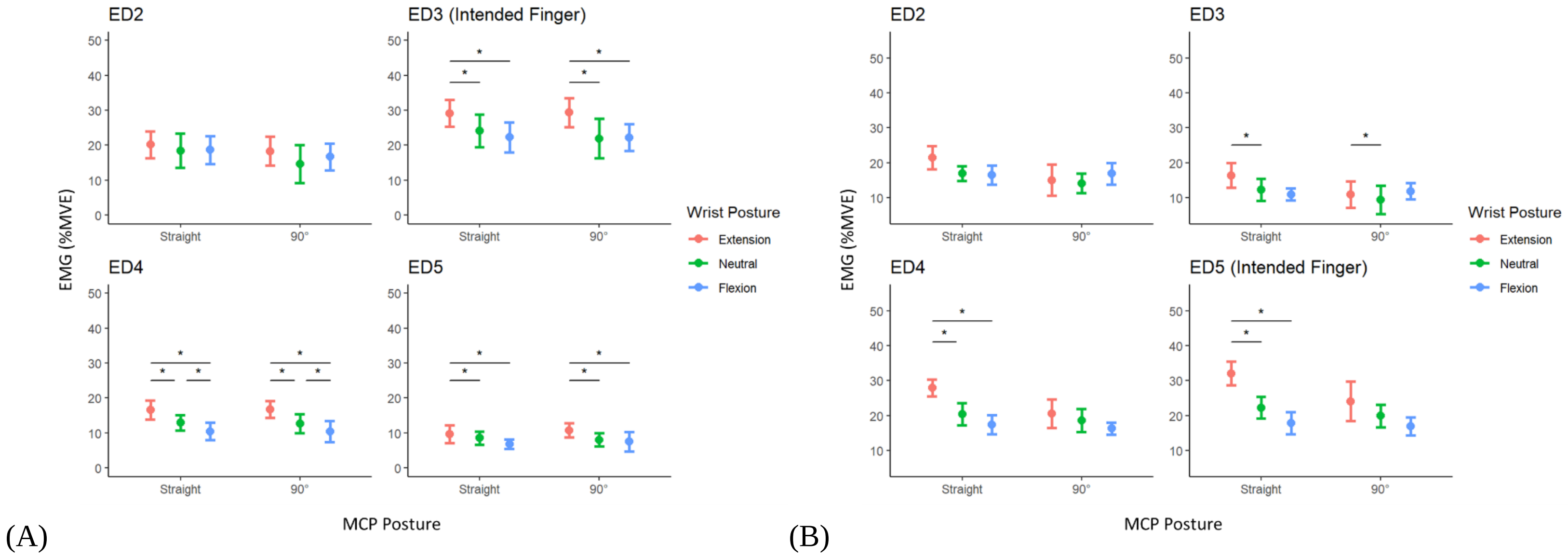


Figure 3.10: Effect of wrist posture on EMG during (A) *Slave Task* (intended finger = middle) and (B) *Slave Task* (intended finger = little). Mean ± 95% confidence interval of EMG (% MVE) of ED2-5 in each of the six wrist and MCP posture combinations are presented. Significant differences between postures are denoted with asterisks.

3.5 Discussion

In this investigation, we predicted the hypothetical mechanical contribution (HMC) towards enslaving across different wrist and MCP postures. We hypothesized that the contribution of juncturae tendineii could be determined by examining the involuntary and voluntary finger extension forces at a given ED activation level. Contrary to our hypothesis, HMCs were primarily outside of the expected range of 0 to 100% (Tables 3.4 & 3.5). This resulted from greater voluntary than involuntary forces at a given ED activation level (Figure 3.6), suggesting that the assumption that the involuntary force contained the full complement of additive neural and passive forces was not true.

The higher voluntary than involuntary force may be explained by differences in the strategy employed by the central nervous system (CNS) to produce finger forces in the *Master* and *Slave Tasks*. Participants were instructed to meet target force and EMG level in the *Master* and *Slave Tasks*, respectively. Thus, the type of outcome measure (i.e. force or EMG) being stabilized differed between the two tasks. According to the principle of motor abundance, the CNS employs different configurations of physiological, kinematic, and/or kinetic variables to accomplish a task (Gelfand & Latash, 1998; Latash et al., 2002; Latash 2012). The CNS, therefore, may have employed different strategies, such as motor unit recruitment or firing patterns, to achieve the target outcome measure during both tasks. As our equation represented a simplified approach for quantifying mechanical contribution, it did not incorporate the possible differences in control strategies between the *Master* and *Slave Tasks*.

Surface EMG amplitude has been suggested to provide a limited representation of neural drive due to the overlap of the positive phase of one motor unit action potential (MUAP) with the negative phase of another MUAP (Day and Hulliger, 2001; Keenan et al., 2005). Additionally, Mottram and colleagues (2005) discovered a significant difference in the reduction of motor unit discharge rates in biceps brachii, despite the lack of a significant difference in the increase of surface EMG amplitudes, during two types of isometric fatiguing contractions requiring the same net elbow moment. They suggested that surface EMG amplitude may not have been sensitive to the small changes in motor unit activity. In our study, ED3 and ED5 were the intended finger extensors during *Slave Tasks*. Despite comparable ED3 and ED5 activity between *Master* and *Slave Tasks,* small differences in neural drive may not have been reflected in surface EMG amplitude (Mottram et al., 2005). This may have resulted in the higher voluntary than involuntary forces at a given EMG level. Nevertheless, it is important to note that motor unit activity is also an estimate, rather than a direct measurement, of neural drive. Currently, it is not possible to quantify the magnitude of neural input to muscles, thus, it can only be estimated via surface or intramuscular EMG (Farina et al., 2010). In our study, surface EMG was used as an estimate of neural drive because surface electrodes were less invasive than intramuscular electrodes.

Based on a simplified representation of the juncturae tendineii (Figure 3.1-B), we assumed a priori that the passive intertendinous connections would not contribute towards voluntary force. However, the higher voluntary than involuntary forces may suggest that the assumption was not true. During voluntary contraction of the intended finger in *Slave*

Task, we assumed that its tendon would pull on the juncturae tendineii, and not vice versa. This assumption may be violated if the adjacent "non-intended" ED tendon excursion also pulled the intertendinous connections as a result of its involuntary muscle activation. Therefore, passive forces may have been transferred via juncturae tendineii to the intended finger tendon, thus, contributing to the voluntary force. Due to the simplified representation of the juncturae tendineii, our equation may not have accounted for this additional force resulting from the pull of the passive intertendinous structures by the "non-intended" fingers.

Involuntary force of the index finger was significantly higher with MCP flexion than straight fingers during *Master* and *Slave Tasks*. This finding may be explained by the greater resting force in the index finger during MCP flexion than straight posture (Table 3.3). The higher resting force was likely due to increased passive force resulting from the greater strain of ED2 and extensor indicis. Furthermore, increased stretch of the juncturae tendineii found between the ED2 and ED3 tendon may have transferred passive force during the resting trial. Specifically, the magnitude of ED3 tendon excursion during MCP flexion may have been greater relative to ED2 tendon, thus, pulling the juncturae tendineii taut. This may have transferred greater passive force to ED2 tendon in the resting trial. Changing MCP posture in the *Master Task* elicited significant difference in force for the index "slave" finger, but not the middle or little "slave" fingers (Figure 3.7). In cadaveric hands, von Schroeder and colleagues (1990) discovered that the mean length of juncturae tendineii found between ED2-ED3 tendons was shorter than the connections between ED3-ED4 and ED4-ED5 (Figure 3.1-A). This anatomical difference in juncturae tendineii length may suggest that during ring “master” finger extension in *Master Task,* the magnitude of ED4 tendon excursion was likely not sufficient to completely stretch the juncturae tendineii between ED3-ED4 and ED4-ED5 tendons. This likely explains the absence of a significant difference in force between MCP postures for the middle and little “slave” fingers during *Master Task*. Future studies may use an apparatus that flexes only one MCP joint, instead all four MCP joints, to further stretch the juncturae tendineii. The higher index finger force observed with MCP flexion may indicate the importance of the juncturae tendineii in enslaving.

Contrary to May and Keir (2018), we did not remove the resting forces prior to the onset of *Master* and *Slave Tasks*. To determine the effects of resting force subtraction on HMCs, we removed the resting force from the involuntary and voluntary force post hoc and re-calculated the HMCs. Despite the subtraction of resting forces, majority of the HMCs remained outside of the expected range of 0 to 100%. Moreover, May and Keir (2018) discovered significantly greater “slave” finger force during ring finger extension at 25% MVC when performed with wrist extension than neutral and flexed postures. In our study, “slave” finger forces were not significantly different between the wrist postures in the *Master Task* (i.e. ring finger extension at 25% MVC). Interestingly, when the resting forces were subtracted during post hoc, we discovered that “slave” finger force was significantly greater with wrist extension than neutral and flexed postures. Therefore, although the subtraction of resting forces produced findings that were consistent with May and Keir (2018), we decided not to deduct the resting forces. This is because when MCP joints were altered from 0° to 90° flexion, or vice versa, the change in ED tendon excursion may be different in each finger, affecting the stretch of the juncturae tendineii and forces transferred via the passive connections. Therefore, if resting forces were subtracted, the effect of the juncturae tendineii on the "slave" finger force would be underestimated.

Consistent with May and Keir (2018), we found greater "master" (ED4) and "slave" (ED3 and ED5) activity with wrist extension than neutral and flexed postures with straight MCP (Figure 3.9). During the *Master Task,* ring "master" finger exerted 25% MVC in each wrist and MCP posture combination. As the finger force was normalized to the maximal force recorded in the neutral wrist with straight MCP, the absolute ring "master" finger force was constant across all wrist and MCP posture combinations. However, the maximal extension force of the ring finger was lower in wrist extension than flexion and neutral postures (Table 3.2). The decreased maximal force capacity of ring finger in an extended wrist posture suggests that greater effort was required to maintain the target force level. Shorter muscle lengths require higher activity to produce a given absolute force than longer muscle lengths (Rack & Westbury, 1969; Heckathorne & Childress, 1981; Vander Linden et al., 1991). This likely explains the higher ED activity in wrist extension than flexion and neutral. Additionally, greater "master" ring (ED4) activity during wrist extension may suggest an increase in neural command to the muscle in that posture. Based on the construct of common neural input innervating different ED compartments (Keen & Fuglevand, 2004; Sanei & Keir, 2013), the possible increase in neural command to "master" ED4 may have produced the higher "slave" ED3 and ED5 activity in the *Master Task* (Figure 3.9).

There are a few limitations in this investigation. Crosstalk is often considered a concern of surface electrodes on forearm, however, we minimized it by placing the electrodes according to literature guidelines (Leijnse et al., 2008; Sanei & Keir, 2013; May & Keir, 2018). In addition, ultrasound was used during pilot testing to confirm the locations of finger extensor muscles. Appropriately spaced electrodes on the forearm have been shown to produce minimal crosstalk in the forearm (Mogk and Keir, 2003). We were not able to record finger flexor activity because it was not feasible given the various postures in the experimental setup and the duration of the protocol. Previous work in our laboratory (May & Keir, 2018) recorded low activation levels in "slave" FDS (under 5% MVE) during ring finger extension at 25% MVC in extended, neutral, and flexed wrist postures. While co-contraction of the finger flexors may have played a small role in our results, our previous work using a similar experimental setup and apparatus suggests that it would have minimal effects.

In conclusion, greater index finger force with MCP flexion during *Master* and *Slave Tasks* may suggest the important role of juncturae tendineii in finger independence. Wrist extension with straight MCP elicited significantly higher ED activity than neutral and flexed postures, supporting the previous evidence in literature. A small proportion of the HMCs were within the expected range of 0 to 100%, indicating that our equation provided a limited representation of mechanical contribution. The complex phenomenon of enslaving in various wrist and MCP postures necessitates further research to accurately determine the contribution of passive connections. If the juncturae tendineii plays a major role in enslaving, we may focus more on improving techniques to surgically remove or alter the connective tissues, thus, increasing finger independence. Conversely, if the intertendinous connections have minimal contribution to enslaving, more efforts may be directed towards developing strategies to enhance the neural independence of individual fingers. Therefore, by broadening our understanding of the passive intertendinous structures, this may help us in making informed decisions on rehabilitation techniques for improving finger control.

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CHAPTER 4: THESIS DISCUSSION

Fingers do not act completely independently and this phenomenon, known as enslaving, has been well-documented in the literature (Zatsiorsky et al., 2000; Sanei & Keir, 2013; van den Noort et al., 2016; van Beek et al., 2018; May & Keir, 2018). A lack of finger independence may affect an individual's dexterity and performance in tasks such as typing, writing, and handling tools. Numerous studies have investigated the mechanisms of enslaving, which includes mechanical and neural factors. The contribution of passive intertendinous connections (i.e. mechanical factors) towards enslaving, however, remains unclear. In this thesis, we made the first attempt at quantifying the mechanical contribution by examining involuntary and voluntary finger forces at a given extensor EMG amplitude.

The current study was primarily motivated by the previous work in our laboratory by May & Keir (2018). The authors predicted that "master" finger extension in a flexed wrist would result in higher force in "slave" fingers than neutral or extended wrist positions. Their hypothesis was based on the passive force-length relationship of ED. At greater ED length (i.e. wrist flexion), they expected higher passive forces produced by the "master" finger extensor and transferred to the "slave" fingers via juncturae tendineii. These findings contrasted their hypothesis and therefore, the authors suggested that the passive intertendinous structures may play a minor role in finger independence. We believe that their finding was a result of the juncturae tendineii not completely stretched due to the straight MCP posture maintained by the participants. In our current study, we used two different MCP postures: straight (0°) and 90° MCP flexion. We hypothesized that by flexing the MCP postures, the juncturae tendineii would be stretched taut, thus transmitting greater passive force across the fingers. We believed that this would help us to better understand the contribution of juncturae tendineii to enslaving.

We initially planned to use a musculoskeletal modeling approach for quantifying mechanical contribution. OpenSim, a musculoskeletal modeling software, provides researchers a platform to create and share models (Delp et al., 2007). Recently, a hand model was constructed by Mirakhorlo et al. (2018b) in OpenSim. This model, however, did not include the juncturae tendineii. We hoped to create a model representing the juncturae tendineii and evaluate the passive force transferred to “slave” fingers. However, we faced a few challenges in estimating the passive forces. First, the stiffness coefficient of the juncturae tendineii, which affects the magnitude of passive force of the intertendinous connections, is currently unavailable in the literature. Second, changes in the juncturae tendineii length would depend on the length of the adjacent extensor tendons. Presently, a mathematical model defining the relationship between the length of juncturae tendineii and extensor tendons has not been developed. As the modeling approach was not feasible given these challenges, we decided to quantify mechanical contribution using a novel experimental paradigm.

In this thesis, an equation was developed for quantifying hypothetical mechanical contribution (HMC). Briefly, by calculating the difference between involuntary and voluntary finger force at a given extensor EMG amplitude, we expected that the remainder of the force could be attributed to juncturae tendineii. This technique was based on a simplified representation of the passive intertendinous structures as well as the use of surface EMG amplitude as an estimate of neural drive. We found only a small proportion of the HMCs were within the expected range of 0 to 100%. Our finding may suggest that the equation provided a limited representation of mechanical contribution in finger independence. Throughout this thesis, we made a few decisions regarding the methodology in the experimental protocol. In the following section, the rationale for these decisions will be presented prior to discussing ideas for future investigations.

4.1 Rationale for Methods

Ring "master" finger force was normalized to its maximal extension forces recorded during the neutral wrist with straight MCP posture. If we were to normalize ring finger force to posture-specific MVCs, then the target absolute force level would be different in each posture. Consequently, any potential changes in "slave" finger force and muscle activity between the postures would be challenging to interpret. This is because it would be unknown whether the changes in "slave" finger force and muscle activity is a result of the change in: (a) wrist and MCP posture and/or (b) absolute ring "master" finger force. However, there was also a limitation associated with normalizing to only one posture. The relative effort exerted by "master" ED4 (ring extensor) was different between postures due to the significant difference in ED4 activity in *Master Task* (Figure 3.9). This difference in relative effort may have influenced the force and EMG observed in the "slave" fingers. The equation in this thesis calculated the difference in forces, rather than muscle activity, of the "slave" fingers (middle and little). Therefore, we decided to maintain the absolute ring "master" finger force constant across the postures by normalizing the force to only the neutral wrist with straight MCP.

We selected 25% MVC as target force level for the ring "master" finger based on our pilot work. When the target force level was less than 25% MVC, we observed that the mean EMG level of the "slave" extensors were low. Due to the small "slave" extensor EMG amplitude, it was challenging to maintain the exertion level at the target EMG amplitude of the corresponding digits during the subsequent *Slave Task*. We also decided not to set the target ring finger force level greater than 25% MVC to minimize the effects of fatigue on EMG amplitude. Additionally, the ring finger was chosen as the "master" finger (in *Master Task*) as it is the least independent digit (Zatsiorsky et al., 2000; Slobounov et al., 2002; Sanei & Keir, 2013; May & Keir, 2018). Greater enslaving by the ring finger allowed for higher "slave" ED activity, thus, resulting in target EMG levels (in *Slave Task*) that were less challenging to maintain.

Static finger extensions, rather than dynamic finger movements, were used to investigate the enslaving phenomenon in this thesis. Dynamic finger movements were not included in our protocol to avoid the influence of variables associated with dynamic contractions, such as force-velocity relationship of muscles, that may further affect our results. As we used a new experimental paradigm to quantify mechanical contribution, we decided to use static finger extensions as the starting point for our simplified approach. If our equation were able to produce all of the HMCs within the expected range of 0 to 100%, future efforts would include dynamic finger tasks.

4.2 Future Investigations

One possible avenue for future research includes cadaveric measurements combined with empirical and musculoskeletal modeling studies. "Master" finger ED tendon of cadaveric forearms may be pulled at different force levels while simultaneously measuring the “slave” ED tendon force. A mathematical model may then be developed to define the relationship between “master” and “slave” ED tendon force. It is important to note that forces recorded in the “slave” ED tendon is a result of the passive forces transferred via juncturae tendineii. A hypothetical relationship between the “master” and “slave” ED tendon force is presented in Figure 4.1. Once the mathematical model is defined, an experimental protocol involving human participants may be conducted. Muscle activity of the “master” and “slave” ED may be recorded while the participants extend the “master” finger at a target force level.

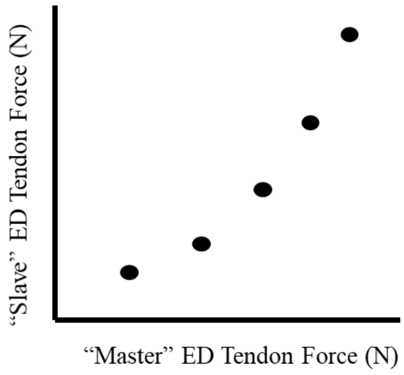

Figure 4.1: Hypothetical relationship between “master” and “slave” ED tendon force may be developed from cadaveric measurements.

Following the experimental protocol, “master” and “slave” tendon forces may be predicted in OpenSim using EMG-driven force estimation techniques with the equilibrium muscle model. The estimated “slave” ED tendon force may be attributed to forces resulting from the neural factors of enslaving. The predicted “master” ED tendon force may be used an input in the mathematical model (developed from the cadaveric study) to estimate the magnitude of the “slave” ED tendon force attributed to the passive forces transferred via juncturae tendineii. The mechanical contribution may then be quantified by expressing the “slave” ED tendon force attributed to mechanical factors of enslaving to the total estimated involuntary ED tendon force. This potential approach involving cadaveric and experimental data as well as modeling techniques may improve current efforts towards quantifying the contribution of juncturae tendineii to enslaving.

4.3 Conclusion

Altering MCP posture significantly changed the index finger force, possibly indicating the importance of passive intertendinous connections in enslaving. Consistent with previous studies, wrist extension with straight MCP produced greater finger extensor activity than neutral and flexed postures. This thesis also proposed an equation for determining mechanical contribution by analyzing involuntary and voluntary finger forces at a given ED activity level. Although the equation produced HMCs which were primarily outside of the expected range, there remains room for improvement in determining the mechanical contribution. Quantifying the contribution of passive intertendinous structures is a challenging endeavour yet crucial for understanding the phenomenon of enslaving. Future investigations including cadaveric measurements combined with empirical and musculoskeletal modeling approaches may elucidate the mechanical contribution in finger independence.

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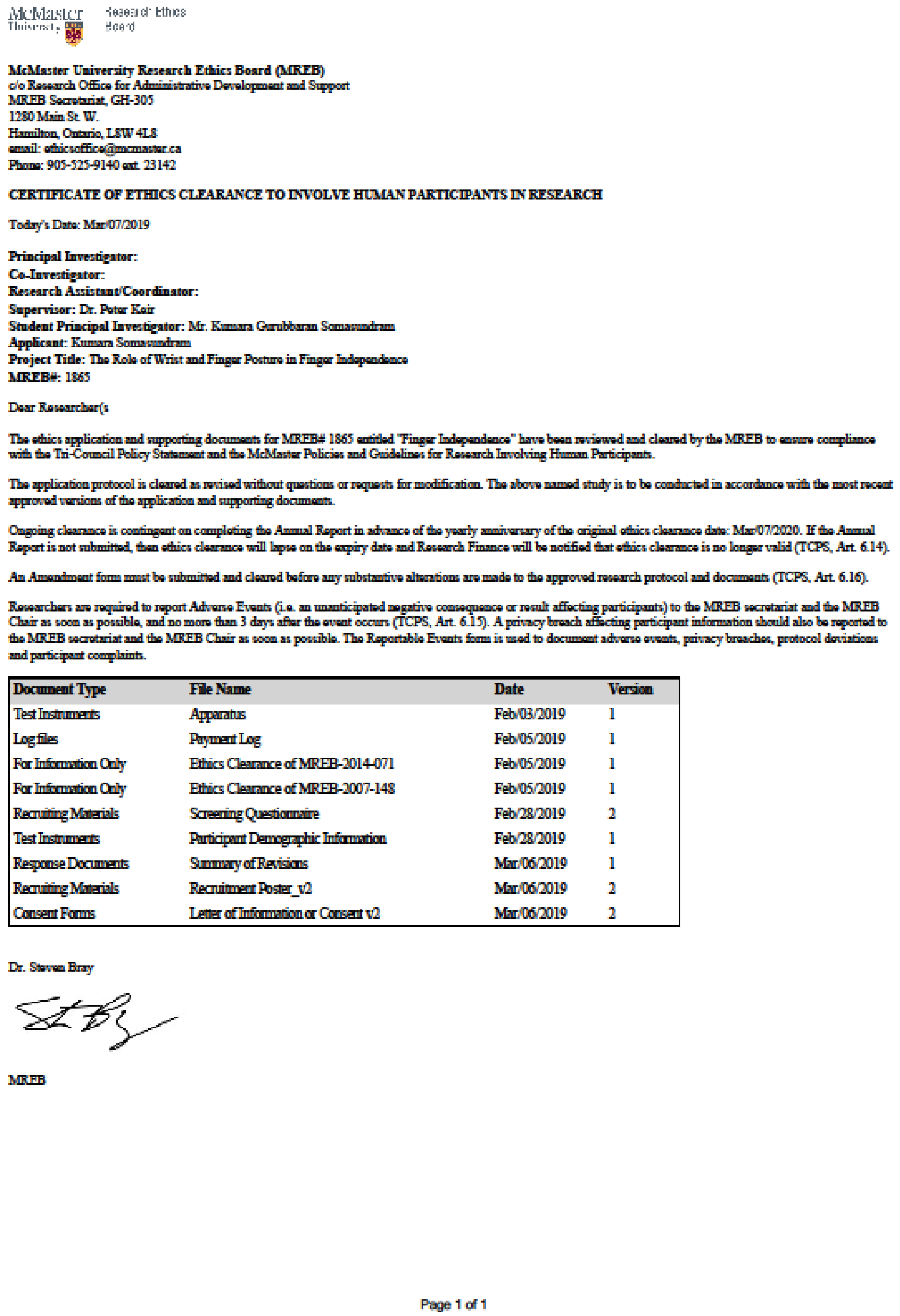
APPENDICES

Appendix A: Ethics Approval



McMaster University Research Ethics Board (MREB)
c/o Research Office for Administrative Development and Support
MREB Secretariat, GH-305
1280 Main St. W.
Hamilton, Ontario, L8W 4L8
email: ethicsoffice@mcmaster.ca
Phone: 905-525-9140 ext. 23142

CERTIFICATE OF ETHICS CLEARANCE TO INVOLVE HUMAN PARTICIPANTS IN RESEARCH

Today's Date: Mar/07/2019

Principal Investigator:
Co-Investigator:
Research Assistant/Coordinator:
Supervisor: Dr. Peter Keir
Student Principal Investigator: Mr. Kumara Gurubbaran Somasundram
Applicant: Kumara Somasundram
Project Title: The Role of Wrist and Finger Posture in Finger Independence
MREB#: 1865

Dear Researcher(s

The ethics application and supporting documents for MREB# 1865 entitled "Finger Independence" have been reviewed and cleared by the MREB to ensure compliance with the Tri-Council Policy Statement and the McMaster Policies and Guidelines for Research Involving Human Participants.

The application protocol is cleared as revised without questions or requests for modification. The above named study is to be conducted in accordance with the most recent approved versions of the application and supporting documents.

Ongoing clearance is contingent on completing the Annual Report in advance of the yearly anniversary of the original ethics clearance date: Mar/07/2020. If the Annual Report is not submitted, then ethics clearance will lapse on the expiry date and Research Finance will be notified that ethics clearance is no longer valid (TCPS, Art. 6.14).

An Amendment form must be submitted and cleared before any substantive alterations are made to the approved research protocol and documents (TCPS, Art. 6.16).

Researchers are required to report Adverse Events (i.e. an unanticipated negative consequence or result affecting participants) to the MREB secretariat and the MREB Chair as soon as possible, and no more than 3 days after the event occurs (TCPS, Art. 6.15). A privacy breach affecting participant information should also be reported to the MREB secretariat and the MREB Chair as soon as possible. The Reportable Events form is used to document adverse events, privacy breaches, protocol deviations and participant complaints.

Document Type	File Name	Date	Version
Test Instruments	Apparatus	Feb/03/2019	1
Log files	Payment Log	Feb/05/2019	1
For Information Only	Ethics Clearance of MREB-2014-071	Feb/05/2019	1
For Information Only	Ethics Clearance of MREB-2007-148	Feb/05/2019	1
Recruiting Materials	Screening Questionnaire	Feb/28/2019	2
Test Instruments	Participant Demographic Information	Feb/28/2019	1
Response Documents	Summary of Revisions	Mar/06/2019	1
Recruiting Materials	Recruitment Poster_v2	Mar/06/2019	2
Consent Forms	Letter of Information or Consent v2	Mar/06/2019	2

Dr. Steven Bray

MREB

Page 1 of 1

Appendix B: Consent Form

March 6th, 2019

LETTER OF INFORMATION / CONSENT

The Role of Wrist and Finger Posture in Finger Independence

Faculty Supervisor/Principal Investigator:
Dr. Peter Keir
Department of Kinesiology
McMaster University
Hamilton, Ontario, Canada
(905) 525-9140 ext. 23543
E-mail: pjkeir@mcmaster.ca

Student Principal Investigator:
Kumara Somasundram
Department of Kinesiology
McMaster University
Hamilton, Ontario, Canada
E-mail: somasukg@mcmaster.ca

Purpose of the Study

Finger control is essential for performing various tasks. 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. This lack of finger independence may affect an individual's dexterity. Finger independence is limited by mechanical and neural factors. The relative contribution of the mechanical factors (such as forces transmitted between the connective tissues between the finger tendons) remains unclear. The purpose of this study is to investigate the relative contribution of mechanical factors towards finger independence in different wrist and finger posture. A deeper understanding of the mechanisms that limit finger independence can help us develop strategies to improve finger control.

Procedures involved in the Research

After introducing you to the apparatus (Figure 1) and protocol, anthropometric measures, such as the length of your hand and arm, height and weight will be recorded. Recording electrodes will then be placed over 4 muscles of the forearm after preparing the skin by shaving and cleaning with alcohol. These electrodes allow us to record the activity in the muscles that control the fingers. To know how active the muscles are, we first need to determine the maximum activity for each muscle through a series of tests. An apparatus will be placed on a 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 the forearm secured on top of the table so that the elbow is bent at 120° and the thumb will be pointing up. You will be required to exert finger forces backward (extension) with the fingers in 4 adjustable padded rings, which will not move while you contract. You will perform 2 maximal contraction trials (extension) per finger. Each maximal contraction will be 5 seconds, and you will be given 60 seconds of rest between each contraction. After maximal force for each finger is determined, you will perform 3 trials of submaximal contractions at 25% of your maximum using your ring finger. There will be a monitor in front of you with two lines. One line is the target and the second line is your force level. Your task is to extend your finger (push back) so that you match the target line. Following that, you will perform 3 trials of submaximal contractions at less than 25% of your maximum using the index, middle, and little finger (each finger will perform 3 trials). Each submaximal contraction will be 5 seconds and you will be given 10 seconds of rest between each contraction. These maximal and submaximal exertions will be performed at three different wrist postures (30° flexion, neutral, 30° extension) and two finger postures (neutral and 90° flexion). In total, you will perform 12 maximal and 18 submaximal contraction trials per finger and you will be participating in the McMaster Occupational Biomechanics Laboratory for less than 3 hours.

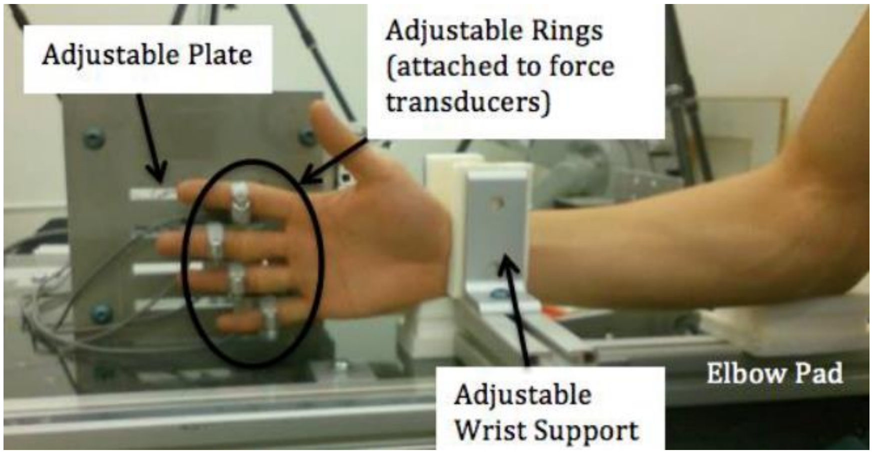


Figure 1: Apparatus that will be used in the experimental protocol. The recording electrodes on the forearm are not shown here.

Potential Harms, Risks or Discomforts

There is minimal risk associated with participation in this study. You may experience some muscle soreness at the back of your hand and/or forearm from the exertions. We try to minimize this with numerous rest breaks during the experiment. Any soreness should not prevent you from your normal daily activities. The electrodes have a hypoallergenic adhesive and although rare, you may experience a temporary reaction to the adhesive from the electrodes. Should you experience any serious discomfort following the study, please contact the Faculty Supervisor, Dr. Peter Keir. Due to the nature of the protocol, you will be excluded from participation if you have been diagnosed with high blood pressure, have a known allergy to adhesives, or have had an injury or pain in the hand, wrist, arm, shoulder or neck. If you have experienced an injury to any of these body parts that currently causes pain, or has a chronic effect on your limb function, you will be excluded from this study.

Potential Benefits

We hope to evaluate the relative contribution of mechanical factors towards finger independence, by manipulating wrist and finger posture. This 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 and the data collected will be used for teaching and research purposes only. You will be asked if you would be willing to have photos and videos of you taken for use in publications and presentations. Photo and video data will only be used with your consent. The information directly pertaining to you will be locked in a cabinet in the lab for a maximum of 15 years. Digital data will be stored in MacDrive of McMaster University and/or encrypted server in Dr. Peter Keir's office for a maximum of 15 years. Only Dr. Peter Keir will have access to this information during that time, after which it will be destroyed.

Participation and Withdrawal

Your participation in this study is voluntary. If you decide to participate, you can decide to withdraw at any time, even after signing the consent form or part-way through the study. You will also be reminded during the testing process that you have the right to withdraw at any time. If you withdraw from the study, your data will be destroyed unless you indicate otherwise. If you decide to withdraw, there will be no consequences to you and you will still receive full compensation.

Information about the Study Results

You may obtain information about the results of the study by contacting Dr. Peter Keir or Kumara Somasundram. An update will be emailed after completion of the study; if you would like an update your email will be required. A summary of the results will be completed by approximately September 2019.

Questions about the Study

If you have any questions about the research now or later, please contact Dr. Peter Keir at 905-525-9140, ext. 23543 or Kumara Somasundram at somasukg@mcmaster.ca

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

McMaster Research Ethics Secretariat
Telephone: (905) 525-9140 ext. 23142
C/o Research Office for Administrative Development and Support
E-mail: ethicsoffice@mcmaster.ca

CONSENT

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

1. [ ] Yes, I would like to receive a summary of the study's results.
Please send them to me at this email address
____

[ ] No, I do not want to receive a summary of the study's results.

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

Photos	Videos
[ ] Yes	[ ] Yes
[ ] No	[ ] No

Signature: ____ Date:
____

Name of Participant (Printed) _____________________________________

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