EFFECT OF WRIST POSTURE AND RATE OF FORCE DEVELOPMENT ON FINGER CONTROL AND INDEPENDENCE

EFFECT OF WRIST POSTURE AND RATE OF FORCE DEVELOPMENT ON FINGER CONTROL AND INDEPENDENCE DURING ISOMETRIC CONTRACTION

By

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ABSTRACT

The anatomical structure of the extrinsic finger muscles suggests that posture may play a role in the production of enslaved forces in the fingers. This phenomenon also appears dependent on contraction conditions. The purpose of this thesis was to determine the effect of: (i) wrist posture on the enslaving effect (EE) during ramp and isotonic exertions, and (ii) the rate of force development on EE and accuracy during ramp exertions. Twelve male participants performed 3 submaximal finger flexion and extension trials with the index and ring fingers at 30° wrist flexion, neutral, and 30° wrist extension. Trials consisted of a 5 second isotonic contraction at 25% MVC (maximum voluntary contraction), and two ramp contractions. Ramp contractions were performed at 25% MVC/s and 10% MVC/s up to 50% MVC, a 0.5 second hold, and decreased to zero at the same rate. Surface electromyography was recorded from the compartments of extensor digitorum and flexor digitorum superficialis and analyzed at 25% of maximum. Wrist posture had a significant effect on EE during extension exertions ($F_{4, 44} > 2.6$, $p < 0.05$); specifically, higher EE, error, and muscle activity were found at shorter muscle lengths. Contraction condition significantly affected EE for both index ($p = 0.001$) and ring finger exertions ($p = 0.001$). In the fingers adjacent to the task finger, descending phase EE was higher than the ascending phase, which appeared independent of muscle activity. This thesis found that, in extension exertions, neural factors affecting EE were dependent on muscle length, while mechanical factors appeared dependent on the type of exertion. These findings further our knowledge of the complex relationship between neural and mechanical control of the hand and fingers.

Keywords: finger, force, enslaving, control, muscle, electromyography

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CHAPTER 1 - INTRODUCTION

The human hand is a remarkable system in which fingers can perform simple or complex tasks such as isolated movement of a single finger or complex synchronous finger motion as required to play the piano. The muscles that control the fingers are divided into two groups: extrinsic (originating outside the hand) and intrinsic (originating within the hand). The extrinsic muscles are larger and associated with greater forces, while the intrinsic muscles of the hand are much smaller and associated with finer movements. Three of the extrinsic finger muscles (extensor digitorum, flexor digitorum superficialis, and flexor digitorum profundus) are comprised of four individual compartments, one for each finger. The tendons that arise from the compartments of extensor digitorum are connected via intertendinous connections called the juncturae tendinei (Von Schroeder et al., 1990). There is evidence that suggests force can be transmitted through these connections to adjacent tendons (von Schroeder et al., 1990; Schieber et al., 2001). Furthermore, due to the number of joints and muscles in the hand, it is extremely rare that only one muscle is activated for any given action. Even during isolated finger movements, other synergistic, and antagonist muscles are unintentionally activated (Sanei and Keir, 2013). When people are asked to move or apply a force with one finger, involuntary forces, or enslaving in non-task fingers occur due to neural and physical connections (Zatsiorsky et al., 2000).

Tension may be transferred through friction in the carpal tunnel, interconnections between tendons, and connections between the muscles. In addition to mechanical connections, neural connections may further add to involuntary force. Despite significantly higher motor unit synchrony within an extrinsic muscle compartment, there is evidence of synchronous firing of motor units between extrinsic muscle compartments; most notably in adjacent compartments (Reilly and Schieber, 2003; Keen and Fuglevand, 2004).

Involuntary finger force production has been quantified using the "enslaving effect" (Zatsiorsky et al., 1998) and the "selectivity index" (Keen and Fuglevand, 2004). The enslaving effect expresses involuntary forces as a percentage of the force produced by the target finger. Zatsiorsky et al. (2000) used the enslaving effect to show that involuntary force production was highest in fingers adjacent to the task finger during single finger flexion exertions. The enslaving effect has also been used to show that independent finger control decreases as force increases (Slobounov et al., 2002a, b; Sanei and Keir, 2013). The selectivity index, used with stimulation of single motor axons, quantifies the distribution of force across the four fingers, where 1.0 represents force produced in a single finger and 0 represents an even distribution of force across all fingers. Keen and Fuglevand (2003) found a relatively high selectivity index (0.7) during weak electrical stimulation of the muscle fibres in extensor digitorum (ED) compartments. Regardless of differences in methodology, the enslaving effect (Zatsiorsky et al., 2000) and selectivity index (Keen and Fuglevand, 2004) have both shown that the index finger is the most independent, while the ring finger is the least independent of the fingers. This has been shown to be the case for both flexion (Zatsiorsky et al., 2000; Wilhelm et al., 2014) and extension exertions (Sanei and Keir, 2013).

In studies that have examined finger independence, most have evaluated isometric static contractions or the ascending phase of force development to a target force.

Enslaving has been found to be similar in both the ascending phase and static phases of ramp contractions (Slobounov et al., 2002a, b), while the descending phase has been shown to have much higher enslaving and antagonist activation (Sanei and Keir, 2013). Those authors attributed the increase in enslaving to the higher muscle activation in non-task compartments during the descending phase. They suggested that motor control, during the descending phase of isometric ramp contractions, differs from ascending or static phases, and that further research was needed to evaluate the differences.

Enslaving may also be affected with different muscle lengths. Since the extrinsic finger muscles cross the wrist, their length varies with wrist flexion and extension. This may cause greater tension in the connective tissues (such as the juncturae tendinei), especially when the wrist is flexed. These intertendinous connections may transfer force to non-task fingers. As the wrist is flexed, the extrinsic extensor muscles lengthen, altering both passive force (Keir et al., 1996) and active muscle force (Hazelton et al., 1975). When tension increases in the extrinsic finger muscle tendons, it may also increase in the juncturae tendinei. If this happens, it is expected to increase enslaving, which would provide further evidence of mechanical restrictions in the fingers. Conversely, when tension is lowered in the extensor tendons (by reducing passive force through an extended wrist), the enslaving seen in the extensors would likely be due to neural connections. Wrist flexion-extension angle can also cause the location of the tendons in the carpal tunnel to change in the palmar-dorsal plane (Keir and Wells, 1999). By flexing or extending the wrist, the tendons in the carpal tunnel shift and bunch together, which likely increases friction between the tendons and alters enslaving. This shift is more prominent when a load is added to the fingers (Agee et al., 1998; Keir and Wells, 1999).

Finger control appears to be affected by the rate of force development. In dynamic finger tracing trials, Kim et al. (2008) found that accuracy to a target trace decreased with slower movement speeds, and enslaving increased with slower movement speeds. Fingers adjacent to the task finger expressed the most enslaving, and the greatest modulation in forces between different movement rates. It is still unclear why there is a difference in enslaving between different rates. Most finger independence studies are performed under isometric conditions. Currently, there are no studies where different rates of force development, and the enslaving effect have been analyzed under isometric conditions. Previous studies, suggest that motor unit properties differ between rates of force development, which suggest differences may exist with isometric exertions (Milner-Brown et al., 1973; Desmedt and Godaux, 1977; De Luca et al., 1982). If the rate of force development has an effect on control and independence, we would expect to see differences in both accuracy and enslaving, under isometric conditions.

It is very important to understand how the compartments of the extrinsic finger flexors and extensors are controlled, and how non-task compartments and fingers are affected with varying tasks. Not only do we gain a better comprehension of the control strategies of the human body, but this research also has applications. Predicting forces in non-task fingers would be useful in biomechanical modeling and ergonomic assessments, especially when investigating cases of muscular overload. Furthermore, understanding how the extrinsic finger muscles are controlled has implications towards tendon transfer surgeries. The neural and mechanical connections influencing finger independence can be evaluated by simple changes in wrist angle, and further examination of the descending phase of isometric ramp contractions. The descending phase has already been shown to include higher muscle activation in antagonist, and non-task compartments, contributing to increased enslaving (Sanei and Keir, 2013). However, the effect to which rate of force development has on control and enslaving in the fingers during ascending and descending phases has yet to be investigated. Activating a single muscle compartment appears to be a very complex task. How individual fingers are controlled is still not completely understood. A better understanding of postures and actions that reduce finger control is needed to delineate loss of control via neural or mechanical restrictions. By examining different rates of force production, we can evaluate their effect on control, and enslaving between the ascending, and descending phases of isometric contractions. Assessment of EMG, enslaving and accuracy, at different wrist angles, and during different rates of isometric force development, would be beneficial for our understanding of the control of the fingers.

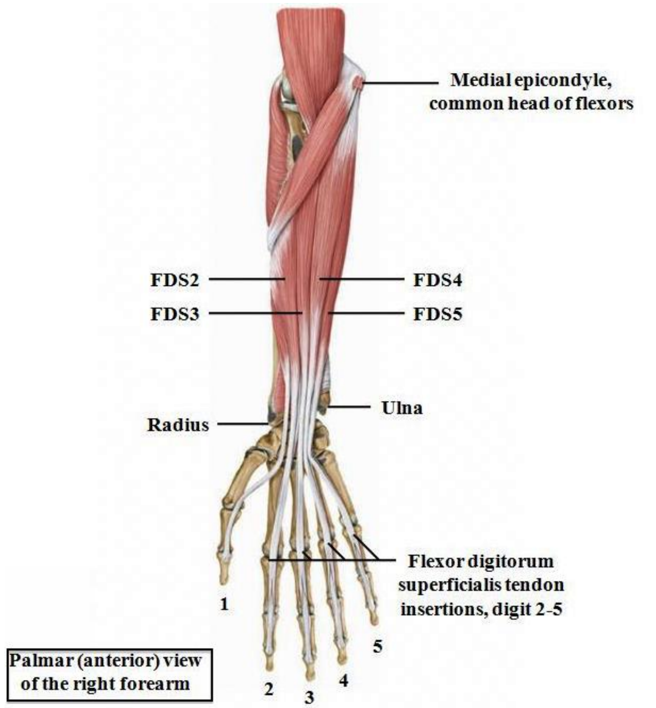
CHAPTER 2 – REVIEW OF LITERATURE

2.1. Anatomy

2.1.1. Extrinsic Finger Flexors

The most superficial of the extrinsic finger flexors is the flexor digitorum superficialis (FDS). The FDS originates from the medial epicondyle of the humerus, coronoid process of the ulna, and on the radius distal to the radial tuberosity. The tendons of the four compartments of FDS travel through the carpal tunnel, and insert on the middle phalanges of the index (2) to little finger (5) (the thumb is considered digit 1). The FDS flexes the proximal interphalangeal, and metacarpophalangeal (MCP) joint of each finger, as well as the wrist. The median nerve innervates all compartments of the FDS.

Just deep to the FDS lies the flexor digitorum profundus (FDP). The FDP originates from the proximal two thirds of the anterior surface of the ulna and adjacent interosseous membrane. The tendons of the FDP also pass through the carpal tunnel and insert on the distal phalanges of the second to fifth digits. The FDP flexes the wrist, MCP, and PIP joints, and is the sole flexor of the distal interphalangeal (DIP) joints. The median nerve innervates the lateral compartments (FDP2 and FDP3), while the ulnar nerve innervates the medial compartments (FDP4 and FDP5).



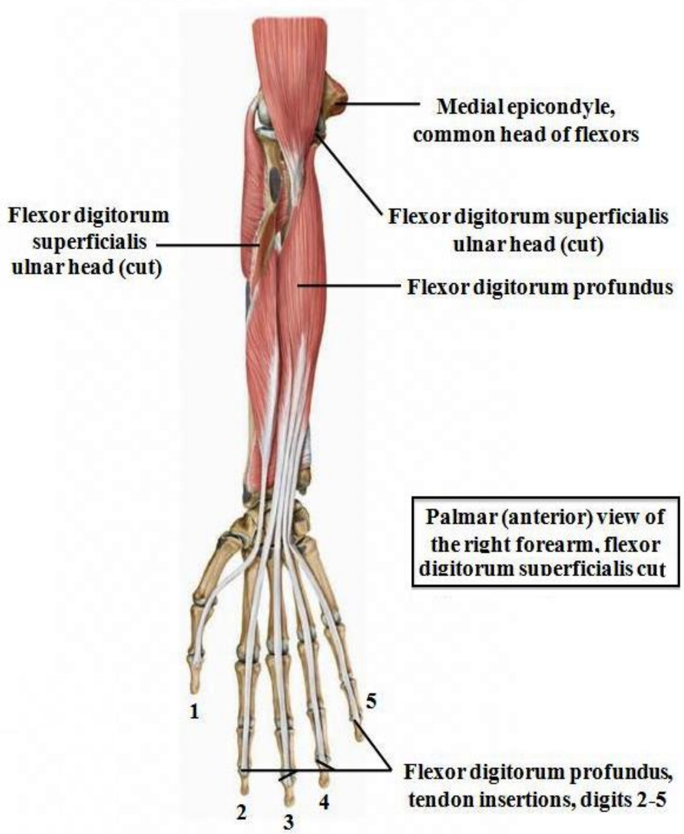


Figure 2.1 Palmar view of the forearm. Top: Origin and insertions of the compartments of the FDS. Bottom: Origin and insertions of FDP (FDS is cut). From Schuenke et al., 2003.

2.1.2. Extrinsic Finger Extensors

Extensor digitorum (ED) originates on the lateral epicondyle of the humerus and acts as the primary extensor of fingers 2 through 5, via radial nerve innervation. The tendons of ED pass through a common synovial sheath deep to the extensor retinaculum before inserting on the dorsal extensor expansion of middle and distal phalanges. In addition to ED, the index and little fingers are also extended by extensor indicis (EI) and extensor digiti minimi (EDM), respectively. EI originates from the posterior side of the ulna and the interosseous membrane and travels under the extensor retinaculum within the same synovial sheath as the ED (Schuenke et al., 2003). The EI inserts on the posterior digital expansion of the second digit, and acts to extend all the joints of the index finger, along with the wrist joint. It lies just deep to the ED. The EDM originates from lateral epicondyle of the humerus along with ED and extensor carpi ulnaris. EDM passes under the extensor retinaculum via its own synovial sheath, causing extension at the wrist and all the joints of the fifth digit through its dorsal digital expansion. The radial nerve innervates both the EI and EDM.

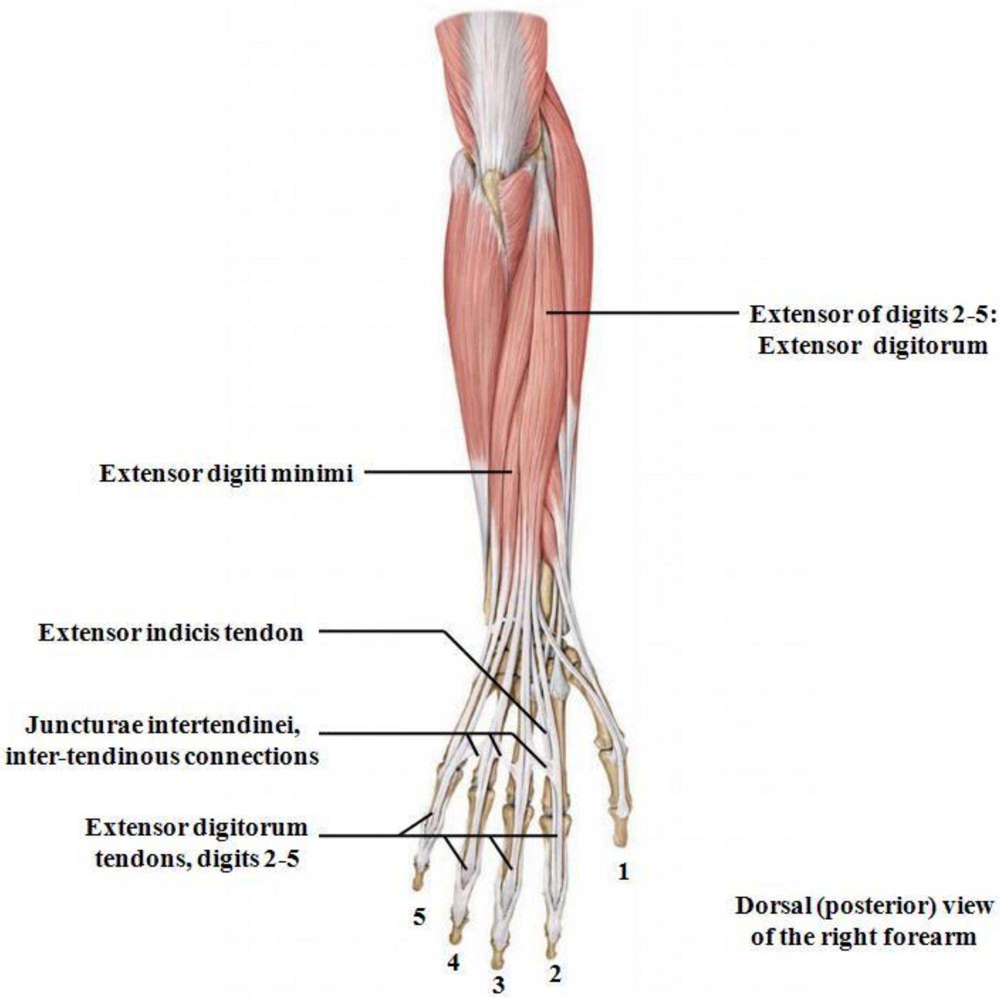


Figure 2.2 Dorsal view of the extrinsic finger extensors, including ED, EI, and EDM. The juncturae intertendinei are clearly visible connecting the tendons of ED. From Schuenke et al., 2003.

2.1.3. Intrinsic Finger Muscles

The muscles originating in the hand are referred to as intrinsic muscles. There are four lumbricals and dorsal interossei muscles, which attach to the first through fourth digits. Three palmar interosseus muscles, with attachments to digits 2, 4, and 5, act to adduct the fingers while the dorsal interossei abduct the fingers. Additionally, all of these muscles act to flex the MCP joint, and extend the PIP and DIP joints. The ulnar nerve innervates the palmar and dorsal interossei, and third and fourth lumbricals, while the median nerve innervates the first and second lumbricals.

The thenar and hypothenar muscles are located superficial to the lumbricals and interossei. There are three hypothenar muscles that insert on the fifth digit, abductor digiti minimi, flexor digiti minimi, and opponens digiti minimi. Together they act to flex the 5^{th} MCP joint, extend the PIP and DIP joints, as well as abduct the little finger. These three muscles are all innervated by the ulnar nerve. The thenar muscles are made up of abductor pollicis brevis, adductor pollicis, flexor pollicis brevis, and opponens pollicis. All of which insert on the proximal phalanx of the thumb/first metacarpal, and work together to provide movement at the carpometacarpal joint of the thumb.

2.2. Surface Electromyography

Recording the muscle activity of the individual compartments of FDS and ED can be a difficult task. The slender shapes of the compartments, as well as their proximity to other muscles carry issues of reliability and crosstalk. Because it is noninvasive, surface EMG is typically preferred (over indwelling) provided it yields clean, reliable signals between compartments. Leijnse et al. (2008a) dissected fifteen forearm specimens to analyze the anatomy of the ED muscle and determine optimal surface electrode placement for each ED compartment. Despite the narrow width of the ED belly, they found that surface EMG was possible for individual compartments. The arising muscle bellies of ED2 and ED4 cover ED3 distally and electrodes are therefore placed proximally, closer to the humero-radial joint (labeled “3” in Figure 2.3). To lessen the crosstalk from ED4, Leijnse et al. (2008a) suggested placing the ED2 electrodes over its radial border ("2" in Figure 2.3), and the ED4 electrodes over its ulnar border ("4" in Figure 2.3) at approximately 45% radial length. The ED5 muscle belly is very narrow and difficult to isolate, thus EDM was determined to be a better candidate to accurately record ("EDM" in figure 2.3). Its location was determined to be just distal (~50% radial length) to the ED2 and ED4 electrodes, and more ulnar deviated.

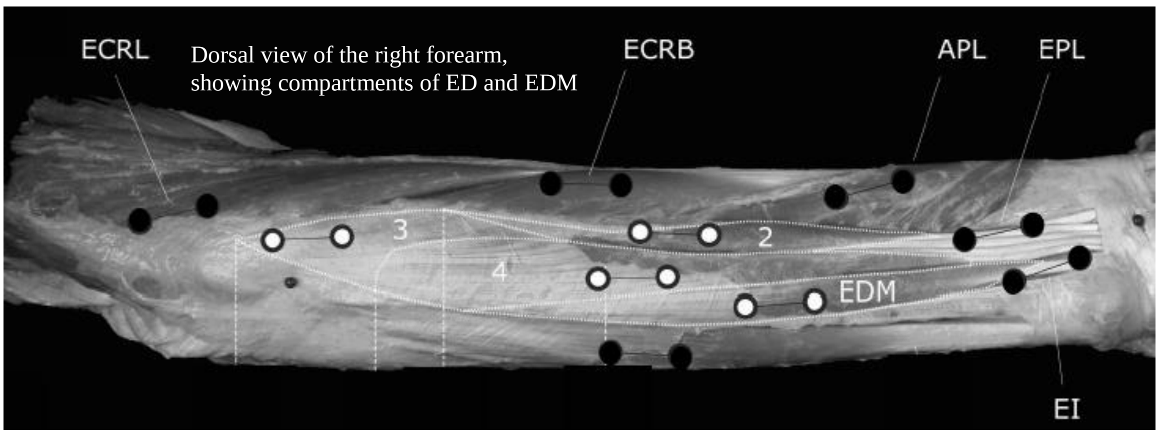


Figure 2.3 Dorsal view of the extensor compartments of a dissected specimen, with suggested electrode placements. White dotted lines outline the compartments of the ED and EDM, and are extended down to mark proximal and distal compartment edges. Open circles represent electrodes for ED, and are labeled by their compartment number. From Leijnse et al., 2008a

Leijnse et al. (2008b) assessed ED compartment activity using electrode placements from their previous study (Leijnse et al., 2008a). EMG was recorded using small (4 mm) bipolar surface electrodes, with a 2 cm interelectrode distance during tapping tests of individual fingers. EMG data of 10 consecutive finger taps were selected based on consistency, and expected readings. Mean peak EMG was calculated for these taps, which were compared between the task compartment, and non-task compartments.

The ED2 electrodes recorded 53% EMG during taps with the ring finger with a medium correlation coefficient (0.59). ED3 electrodes recorded only 14% EMG, during 2nd digit tapping, with a correlation coefficient of 0.91. ED4 electrodes received moderate EMG for tapping with digits 2 and 3 (30% and 28% respectively), but 48% (from EDM) during 5th digit taps (correlation coefficient = 0.85). Non-task EMG for EDM was the worst, recording moderate EMG for taps with digit 2 and 3 (35% and 13%, respectively), and 93% during taps with digit 4 (correlation coefficient = 0.41). However, during taps with digit 5, EMG of the EDM could be well recorded, with minimal EMG in adjacent compartments.

Mogk and Keir (2003) used a cross-correlation function to determine the amount of common signal between surface electrodes circumferentially placed around the forearm during pinch and grip tasks. A cross-correlation function is commonly used with EMG to determine the magnitude of common signal between electrode pairs as a function of time lag (Winter et al, 1994). Mogk and Keir (2003) placed 7 bipolar (1 cm diameter recording surface) surface electrode pairs around the circumference of the forearm. Pairs had a centre-to-centre interelectrode spacing of 2.5 cm, and 3 cm spacing between each pair. The common signal between adjacent electrodes pairs ranged from ~33-41%, and dropped to <11% for 6 cm electrode pair spacing, similar values were found by Winter et al. (1994). Furthermore, there was only about 2% common signal between the flexor and extensor electrode pairs. The low common signal found between the flexors and extensors suggests minimal crosstalk.

In summary, the compartments of FDS and ED can be analyzed reliably using surface EMG (Leijnse et al., 2008b). Additionally, with accurately placed electrodes, crosstalk should be minimized between electrode pairs (Mogk and Keir, 2003).

2.3. Limitations to Finger Function

Despite the dexterity of human fingers, there are restrictions that limit finger control. These limitations are due in part, to the multiple muscles controlling each finger, which produce such high dexterity.

2.3.1. Mechanical connections of the extrinsic finger flexors and extensors

It is commonly reported that the interconnections between the distal tendons of the extrinsic finger extensors are partially responsible for limited movement of the digits through flexion and extension (von Schroeder et al., 1990; Schieber et al., 2001). The connective tissue called the juncturae intertendinei (also known as juncturae tendinei), is located just proximal to the MCP joint, and is unique to the extensors (Kaplan, 1959; Leijnse et al, 2008b). In a dissection study of 40 cadaver hands, the juncturae tendinei differed between metacarpals, and could be classified into 3 types (Von Schroeder et al., 1990). Type 1 was very filamentous and was found in 88% of the second intermetacarpal space (between metacarpals 2 and 3). Type 2 was thicker than type 1 and mainly found in the third intermetacarpal space (40%). Type 3 tendinei were the longest, most narrow and thickest of the three types, and were mainly found in the fourth intermetacarpal space (20%). This type of tendinei ran at a more oblique angle than the other connections. Keen and Fuglevand (2003) believed that the juncturae tendinei might limit independence in extension. They measured extension forces of each finger (preloaded with 2 N) during stimulation of individual compartments, and found force unloading in ED4 during ED5 compartment stimulation. The researchers attributed the unloading to the oblique angle of the type 3 juncturae tendinei, which would result in unloading during ED5 stimulation, but not ED4.

Kilbreath and Gandevia (1994) tested the FDP for mechanical connections by passively displacing each distal phalanx when the forearm, and hand were anaesthetized by ischaemia. They found that other digits did not move when the digit acted on was flexed or extended. This indicates that there are no interconnections between the FDP tendons in humans, or if there are, that they play an insignificant role in tension distribution across the fingers.

Other modes of force transmission have been reported. Force transmissions from the muscle to skeleton that are not through the muscular origin and insertion, have been called epimuscular myofascial pathways (Maas and Sandercock, 2010). The force transferred through these epimuscular myofascial pathways has been categorized into (i) *intermuscular*, in which force is transmitted through the connective tissue between adjacent muscle bellies, and (ii) *extramuscular*, in which force is transmitted between the epimysium of a muscle and adjacent non-muscular structure (i.e. tendon/tendon sheath). Maas et al. (2004) found that force produced by the extensor digitorum longus (EDL) in rats changed when its relative position changed, despite an unchanging absolute length. These changes in force were attributed to epimuscular myofascial pathways, and suggest that isometric muscle force is dependent on the muscle position relative to its surroundings, as well as its relative length. It is possible that the same phenomenon may occur in the human forearm where individual isometric flexion and extension of fingers may pull on adjacent muscles through connective tissues.

2.3.2. Neural connections of the extrinsic finger flexors and extensors

Neural connections can also limit the independence of fingers (Schieber and Santello, 2004). Keen and Fuglevand (2004) determined the common input strength (CIS) of the extrinsic finger muscles by finding the magnitude of the central peak of the cross-correlation function. In low force isometric extension trials, motor unit synchrony in the ED was greatest when the needle electrodes were within the same compartment (CIS within = 0.7 ± 0.30, between = 0.4 ± 0.22; Keen and Fuglevand, 2004), regardless of compartment. The same was found for the FDS (Figure 2.4; CIS within = 0.45 ± 0.30, between = 0.23 ± 0.19; McIsaac and Fuglevand, 2007). Winges and Santello (2004) used the same process to report CIS values between compartments of the FDP. However, they found similar CIS values across multiple compartments (2 and 3 degrees of separation) to those in adjacent compartments ($p > 0.05$). Indicating, that differences exist between the neural input to the FDP, and ED/FDS. Where compartments of FDP are more likely to act together, a recurring feature of multi-digit grasping task.

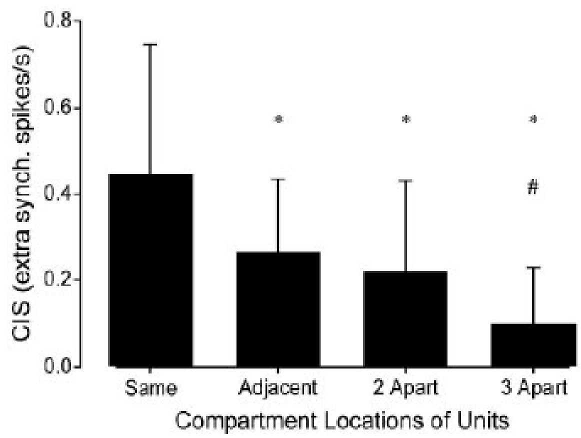


Figure 2.4 Common input strength (CIS) within and between compartments in the FDS. *Significantly different ($P < 0.05$) from intracompartmental pairs. #Significantly different from adjacent-compartment pairs. From McIsaac and Fuglevand, 2007.

Uniform motor-unit synchrony across compartments of the FDP could be in part due to the smaller size of FDP which could lead to greater “neural spillover”, where the neural command to contract in one compartment is sent to motor units in other flexor compartments as well (Kilbreath and Gandevia, 1994). In the extrinsic finger flexor muscles, spillover appeared to be greater in FDP (Reilly and Schieber, 2003; Winges and Santello, 2004) than FDS (McIsaac and Fuglevand, 2007). A comparison of extracompartmental synchrony showed that, FDP had higher CIS values than FDS for every combination between compartments (Figure 2.5; McIsaac and Fuglevand, 2007). This suggests that of the flexor muscles, FDS appears to have more neural independence than FDP.

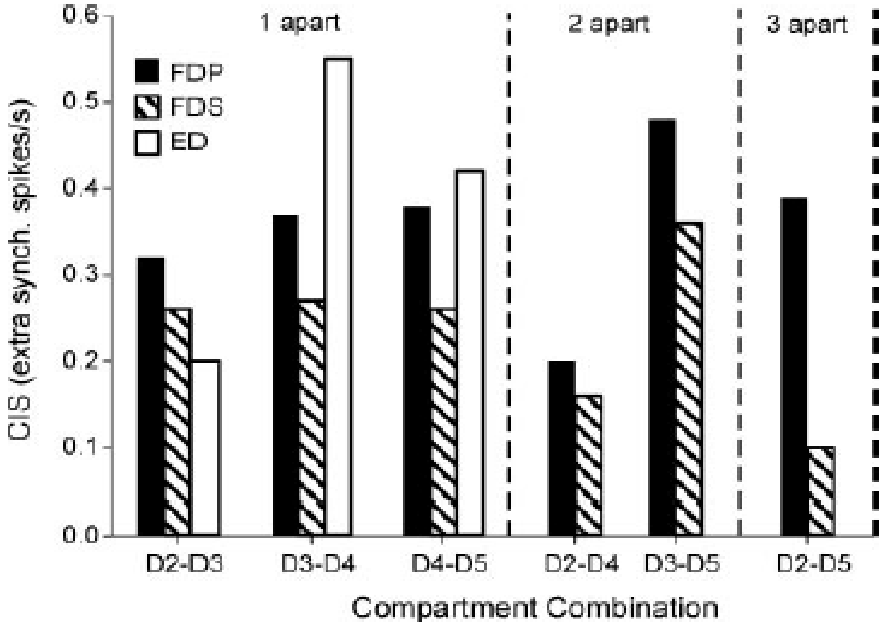


Figure 2.5 Extracompartmental comparison of motor unit synchrony of FDP, FDS, and ED. From McIsaac and Fuglevand, 2007.

Between-compartment synchrony was highest in the neighbouring compartments of the ring finger, and lowest in the adjacent compartments of the index finger. This relationship was seen for all three extrinsic finger muscles, providing evidence from several sources, that the index finger is the most independent, and the ring finger is the least independence (Reilly and Schieber, 2003; Winges and Santello, 2004; Keen and Fuglevand, 2004; McIsaac and Fuglevand, 2007). This was also seen through greater enslaving effect (involuntary forces) in adjacent fingers, which were highest in the ring finger exertions, and lowest with index finger exertions (Zatsiorsky et al., 2000; Slobounov et al., 2002b; Sanei and Keir, 2013).

During isometric flexion and extension trials, antagonist activation can also affect the enslaved forces. Sanei and Keir (2013) noted higher antagonist activity in the ED compartments during MCP flexion tasks than in the FDS during extension tasks. Reilly and Schieber (2003) also found FDP antagonist activity in extension trials, which was greater in the compartments adjacent to the target finger (i.e. for digit 3 extension, FDP2 and FDP4 showed higher antagonist EMG). This activity is expected to reduce extension force in non-instructed digits, otherwise known as enslaving forces.

The human nervous system appears to activate the target compartments of ED and FDS very well (Keen and Fuglevand, 2004; McIsaac and Fuglevand, 2007). Of the fingers the index appears to be associated with the lowest amounts of neural coupling, while the ring finger tends to have the largest. Finally, neural control of the antagonist compartments appears to differ between flexion and extension exertions.

2.4. Measuring Finger Independence

Two methods have been primarily used to evaluate independent movement of the fingers through force measurements. Used with stimulation, the "selectivity index" ranks the force distribution between the fingers, where 1 represents force produced strictly in one finger, and 0 designates force evenly distributed across all fingers. The enslaving effect (EE) reports forces generated by the non-target fingers as a percent of the maximal force produced by that finger.

2.4.1. The Selectivity Index

Keen and Fuglevand (2003) analyzed the distribution of force in the ED through stimulation of the individual compartments, and independent force production of the fingers was assessed through use of the selectivity index. Participants' forearms were placed in a neutral, mid pronation-supination posture, and fingers held in 90° MCP flexion with each digit eliciting 2 N of extension force. The ED was then stimulated with a tungsten microelectrode, at 2-5mm intervals across the entire medial-lateral width of ED, and at distal, middle, and proximal regions. Participants did not actively produce any contraction throughout the protocol. The selectivity index was calculated as follows:

$$\text{selectivity index} = d/\,d_{\max}$$

$$\text{where } d = \sqrt{\sum_{i=1}^{n}(\tau_i - \tau_u)^2} \quad \text{and } d_{\max} = \sqrt{(1-\tau_u)^2 + \sum_{i=2}^{n}(\tau_u)^2}$$

Equation 1. From Keen and Fuglevand, 2003

where $\tau_u = 0.25$, and τ_i represents the fraction of force produced on each finger (Keen and Fuglevand, 2003). The mean selectivity index for all sites tested was 0.70 ± 0.21, while digits 2-5 yielded 0.75 ± 0.11, 0.64 ± 0.17, 0.63 ± 0.11, and 0.99 ± 0.24, respectively. These indices were fairly high, indicating adequate independent force generation of ED on the fingers. The higher selectivity index found in the little finger can be attributed to six sites that produced values greater than 1.0. This was associated with unloading, or flexion force (assigned as negative force in the equation above), in digits 3 and 4. However, the mean values were most likely underestimated since the microelectrode was moved in small increments across ED. This resulted in the electrode occasionally bordering two compartments, and stimulating muscle fibres belonging to both compartments, which would have lowered the selectivity index. These selectivity indices show that a significant degree of motor unit synchrony exists within the compartments of ED. Plus, when the ED5 compartment was stimulated adjacent fingers had a tendency to unload.

2.4.2. The Enslaving Effect

Finger enslaving occurs when a subject is asked to flex or extend a finger, termed the “task finger”, and other fingers are involuntarily activated, thus acting as “slaves” (Zatsiorsky et al., 1998). Zatsiorsky et al. (2000) continued their research on the enslaving effect using an apparatus with a loop for each finger that could be adjusted to any distance along the digit. Placing the loops at different points on the finger acted to engage different muscles. For example, the most distal loop (around the distal phalanx) would require the FDP, FDS, and intrinsic muscles to be active, while around the PIP only required the intrinsic (Li et al., 2000). Zatsiorsky et al. (2000) had participants perform maximal MCP flexion with each finger, and targeted different muscles through loop location. During single finger tasks, similar enslaving forces were seen for all loop positions along the finger suggesting a similar enslaving effect between the FDS, FDP, and single-digit intrinsic hand muscles. The main finding from this study was that enslaving was higher in adjacent fingers. Additionally, they concluded that the enslaving was mainly due to neural restrictions, because similar enslaving was seen with exertions involving mainly the extrinsic flexors and the intrinsic flexors. The force produced by each muscle was determined using the biomechanical model based on loop location (Li et al., 2000). The conclusion that enslaving is mainly due to neural restrictions may only be true in flexion since intertendinous connections between the finger flexors do not significantly distribute tension (Kilbreath and Gandevia, 1994). If intertendinous connections have an effect on enslaving it would likely be seen in extension when the juncturae tendinei is stressed. This has been reported with the unloading seen in digit 4 with stimulation to ED5 (Keen and Fuglevand, 2003), as well as the higher enslaving forces seen in isometric extension (Sanei and Keir, 2013).

2.5. Finger Independence During Submaximal Exertions

The enslaving effect is not isolated to the production of maximal forces from the task finger, it has also been seen in submaximal efforts. Slobounov et al. (2002a) examined enslaving in submaximal force production by having participants press down on four load cells, aligned with each fingertip. For each finger, participants ramped up to 25, 50 and 75% maximal voluntary contraction (MVC) by following a trace at a constant rate of 50% MVC/second, then held the target force resulting in a 5 second trial. They found that mean absolute error increased as the target force increased ($p < 0.001$), regardless of finger. Furthermore, enslaving significantly increased as target force increased for the task finger of all trials ($p < 0.001$). In all trials, enslaving was lowest in the index finger, indicating greater independence, followed by the little, middle and finally ring finger.

Enslaving is not exclusive to static tasks, it has also been found in dynamic tasks. Kim et al. (2008) analyzed enslaving in dynamic motions, where participants followed a trace to 45° MCP flexion and then extended to 0°. They found that accuracy, defined root mean square deviation (RMSD) from the target trace, increased with faster rates (30-45°/s), but was not significantly different at rates of 30°/s or less. They also found a significant increase in total enslaved force (total force production across all non-task fingers) as movement rate decreased to 18°/s. Accuracy and total enslaved force appear to be inversely related as a function of movement rate, with MCP finger flexion tasks to

45° flexion. A rate of 30°/s should yield the best finger control since it's the lowest rate before significant increases in RMSD, and minimizes total enslaved force.

Kim et al. (2008) also measured enslaving at various time-points throughout dynamic finger flexion. Enslaving indices were defined as change in force of non-task fingers divided by angular change of the task finger. By doing this, the researchers could break both the flexion, and extension phases into three equal parts (10-36%, 37-63%, and 64-90% of the range of motion). Consistently, the enslaved forces were always highest in the most flexed position of all fingers. This was true regardless of the movement direction (flexion or extension). This supports the premise that, in the flexion compartments, our fingers have the best independent control at lower levels of flexion, due to lower levels of enslaving. Differences between finger flexion (0° to 45° flexion), and finger extension (45° flexion to 0°) were apparent for the overall movement. Enslaved forces were always in the flexion direction, but were significantly higher over the flexion phase of contraction than the extension phase. This indicates that the enslaving effect is not symmetrical when a finger is moved in flexion, and when it is moved in extension.

New evidence from an isometric study shows that, at similar relative force levels, enslaving was always higher in extension, regardless of exertion mode (isotonic, ascending ramp, or descending ramp contraction; Sanei and Keir, 2013). The researchers believed the lower independence seen in extension could be due to greater intertendinous connections (juncturae tendinei), and the two extrinsic finger flexors (FDS and FDP). Having two sets of finger flexors allows the central controller to activate one or both in a way to decrease total extension enslaving. This might also explain why the index finger had the greatest independence in extension, since it is also controlled by the extensor indicis (EI), which does not have any tendinous attachments to adjacent tendons. The little finger is also controlled by a second muscle (EDM), but did not experience greater independence. This is likely because EDM has tendinous connections to the tendon of ED5, forcing them to act together (von Schroeder et al., 1990). Furthermore, the thickest part of the juncturae tendinei occurs between the tendons of ED4 and ED5, increasing the amount of force transfer to the tendons of the little finger (von Schroeder et al., 1990).

Training has also been shown to have an effect on finger control. Slobounov et al. (2002b) examined control differences between experienced pianists and age-matched controls, in submaximal flexion tasks. The pianists had 10 years experience and practiced daily, they were considered to have better finger control than their age-matched counterparts as shown by Parlitz et al. (1998). On the other hand, non-musicians typically use their index finger more than their ring finger for daily tasks, suggesting their index finger should have better control than their ring finger. They found that mean absolute error was significantly lower in musicians during the ascending ramp phase of contraction ($p < 0.05$) than non-musicians, but not significantly different for the static phase. Enslaving was significantly higher in the ring finger than index in non-musicians, but no significant difference existed in musicians. These results suggest that piano training improved accuracy during the ascending ramp phase of force development, but not during constant force. Moreover, experienced pianists or related high level training appeared to be associated with greater finger independence (Figure 2.6; Slobounov et al., 2002b).

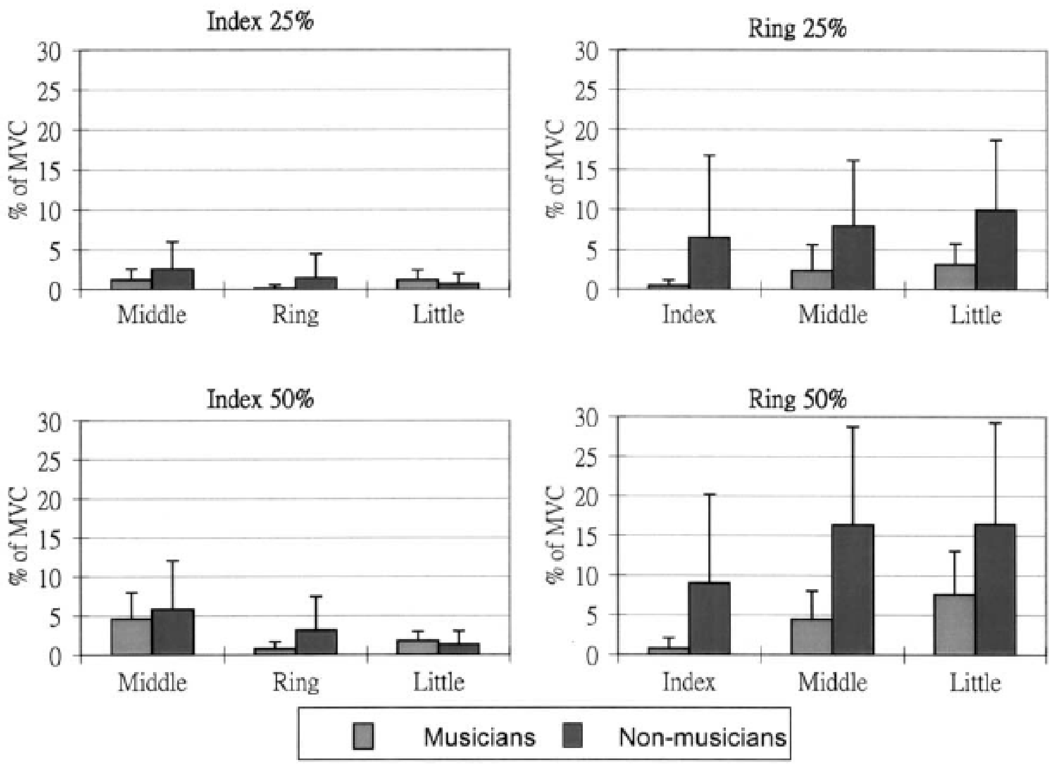


Figure 2.6 Mean percent enslaving between musicians and non-musicians in 25 and 50% MVC ramp contraction trials. Notice the similar values between the index and ring trials of the musicians. From Slobounov et al., 2002b.

Throughout all trials, Slobounov et al. (2002b) found little difference in motor-related cortical potentials (MRCP) amplitudes between musicians and non-musicians for the static phase of the contraction. However, from 600 ms prior to force initiation, and during the ramp phase, musicians always had higher MRCP amplitudes at force levels of 10 and 25% MVC, but not at 50% MVC. The MRCP amplitudes show that in experienced pianists, central control of these fingers has developed differently for low force tasks (10 and 25% MVC) between musicians, and controls that do not practice individualized movement of these digits as frequently. In addition, differences in MRCP amplitude between fingers for non-musicians were observed. This suggests that there is different electro-cortical activation in experienced musicians, and in frequently used fingers, such as the index, in non-musicians.

Control of the fingers can change drastically depending on the mode of contraction. Sanei and Keir (2013) analyzed submaximal isometric contractions for flexion and extension ramp contractions up to 75% MVC in each finger. During 25% MVC flexion exertions, AEMG of the antagonist ED compartments was always significantly higher in the descending phase, than the ascending or isotonic phases (Figure 2.7). However, the increased ED activity did not counterbalance the non-task compartments of FDS, leaving greater enslaving forces in descending exertions. The antagonists are likely activated to help stabilize the finger, which appears unstable during descending contractions. This suggests that a different control mechanism may be used during the descending phase of ramp contractions. At lower levels of force (50% MVC and below), exertion mode had a large effect on the enslaving effect. Participants had difficulty controlling the force during the descending phase of the ramp contraction, which was evident in larger enslaving forces in the descending phase as well as in the raw data traces. In contrast, exertion mode did not seem to effect enslaving at high force levels (75% MVC). It appears exertion mode plays a larger role in control at force levels of 50% MVC and below (Sanei and Keir, 2013).

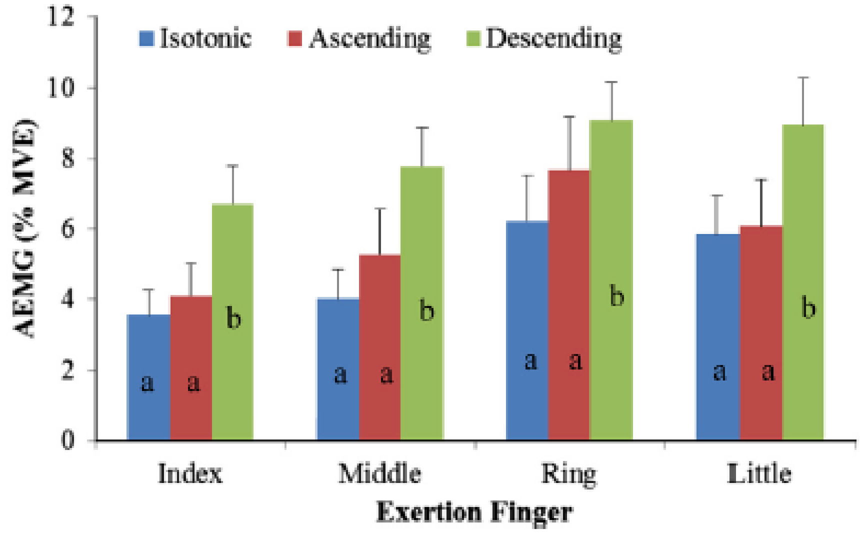


Figure 2.7 AEMG of the antagonist ED compartments during 25% MVC flexion exertions. Different letters denote significant differences between exertion modes ($p < 0.05$). From Sanei and Keir, 2013.

2.6. Testing the Mechanical and Neural Connections of the Fingers

2.6.1. Wrist Posture

Wrist deviation from neutral can also put greater strain on the structures involved in finger movement. By flexing the wrist, the extensor tendons are lengthened, and passive force would necessarily increase in the tendons (Keir et al., 1996). This would also increase the tension throughout the juncturae tendinei, since they are connected to the ED tendons. Thus we might expect greater enslaving effects in this wrist posture, with isometric finger extension force. Conversely, passive force would increase in the flexor tendons when the wrist is extended (Keir et al., 1996). However, it is expected that the enslaving effects seen in this posture with isometric finger flexion force, will be less than in wrist flexion with isometric extension force, since there are no intertendinous connections, or their effects are insignificant (Kilbreath and Gandevia, 1994). By manipulating the musculotendinous lengths of the extrinsic finger muscles through wrist posture, mechanical connections believed to affect enslaving would be strained, and enslaving should change.

In association with changes in passive force, Hazelton et al. (1975) showed that active force produced by the extrinsic finger flexors changes with wrist angle. With wrist flexion (two-thirds of maximum flexion), the extrinsic finger flexors produced lower forces than in wrist extension (two-thirds of maximum extension). However, flexion force in both postures was lower than in neutral, suggesting that the peak of the active force-length curve lies somewhere between two-thirds maximum flexion and extension. Additionally, percent of total force produced by each finger was constant across all wrist postures (Hazelton et al., 1975). This suggests that changing wrist postures has an equal effect on the compartments of the extrinsic finger flexors for similar actions, since percent total force did not change in individual fingers across wrist postures.

When the wrist angle is altered, the extrinsic finger flexor tendons shift within the carpal tunnel. In a magnetic resonance imaging (MRI) study by Keir and Wells (1999), tendons migrated toward the flexor retinaculum with 45° wrist flexion, however in 20° wrist extension the tendons were located more centrally in the carpal tunnel. With only 20° wrist flexion the tendons within the carpal tunnel were shown in close proximity, and the addition of a load (10 N pinch grip) resulted in tighter curvature around the flexor retinaculum. The change with the addition of a load was even larger for greater flexed wrist angles, but was not seen in wrist extension (Keir and Wells, 1999). This work supports the findings by Agee et al. (1998), who also noted changes in FDS tendon displacement with wrist angle. The tighter grouping of the tendons in the carpal tunnel with wrist flexion and a load, could lead to increased friction that may increase enslaving forces, which would be limited in wrist extension.

2.6.2. Rate of Force Development

Rate of force development may have an effect on finger control. Dynamic finger flexion trials have shown significant changes in accuracy, and enslaving with movement speed (Kim et al., 2008). They found that EE was dependent on both the direction of movement, as well as the rate of motion within the task finger, as previously discussed (see *Finger Independence During Submaximal Exertions*). However, the EE has yet to be investigated across different rates of isometric force development. Force can be generated through two methods, motor unit recruitment, or rate coding. According to Henneman's size principle, slow twitch fibres are recruited first, and larger motor units are recruited as contraction force increases (Henneman et al., 1957). Decruitment occurs in the reverse order from which they were recruited (De Luca et al., 1982). There is some debate as to when a motor unit is decruited. Some found they are decruited at higher force levels than they are recruited (Milner-Brown et al., 1973; De Luca et al., 1982), and others found no difference between these force levels (Oya et al., 2009). However, all of these studies agree that the same motor units decruited at significantly lower discharge rates than they were recruited. There are differences in the control mechanisms between the ascending and descending phase of isometric ramp contractions, as seen by the motor units. Further research is needed to analyze the differences in control mechanisms between these phases.

The rate of force development has also been shown to have an effect on motor unit activity. There is evidence to suggest that, as rate of force development increased, the force at which motor units were recruited decreased (Budingen et al., 1976). These findings support those of Milner-Brown et al. (1973), who also noted a different firing rate pattern as rate of force development increased in the first dorsal interosseous muscle (FDI). In the FDI, the same motor unit was recruited at a lower force (lower recruitment threshold), and with a higher discharge rate during the fastest rate of force development. Interestingly, there was no difference in firing rate with different rates of force in the descending phase. More recently, a study by Ricard et al. (2005) analyzed differences in surface EMG between isometric ballistic (610.2 ± 123.1 Nm/s), and ramp (212.3 ± 155.6 Nm/s) contractions to 100% MVC in the gastrocnemius. They found greater EMG amplitude with ballistic contractions, compared to ramp contractions, at torques less than 75% MVC. The highest EMG amplitude was found at 25% MVC during ballistic contraction. Motor units appear to elicit higher initial firing rates for faster contractions (Milner-Brown et al., 1973). Motor unit recruitment and firing rate appear dependent on rate of force development, and type of exertion (i.e. ascending/descending ramp contraction; Milner-Brown et al., 1973; De Luca et al., 1982; Ricard et al., 2005). This may lead to differences in enslaving, and accuracy to a trace.

2.7. Summary

Enslaving between fingers has been extensively analyzed under a wide range of conditions (Zatsiorsky et al., 2000; Slobounov et al., 2002a, 2002b; Kim et al., 2008; Sanei and Keir, 2013). These effects have been attributed to neural connections and mechanical restrictions. The enslaving effect can be used as a tool to assess independence and control among fingers. This, combined with EMG from the compartments of FDS and ED, can provide insight into how the fingers are controlled during different types of isometric contractions, specifically the descending phase of ramp contractions. Sanei and Keir (2013) have shown that, during the descending phase, there are greater enslaving forces, and higher antagonist activation. Suggesting different control mechanisms in the descending phase of ramp contractions, resulting in increased difficultly. By analyzing the descending phase, we can gain a better understanding of the relationship between neural drive and the compartments of FDS and ED. Further investigation of the control mechanisms in the descending phase is required.

The wrist posture may also affect the FDS and ED muscles, and indirectly finger control, since the extrinsic finger muscles cross it. By increasing tension in the juncturae tendinei, through a flexed wrist posture, the enslaving effect may increase, providing evidence for mechanical restrictions on the fingers. The control methods of the fingers are also dependent on rate of force development, which has been shown to affect motor unit firing rate patterns. These patterns are different in the ascending and descending phase of force production, which could lead to differences in the enslaving effect. The effect that wrist angle, and rate of force development, have on the enslaving effect and finger control, is the subject of active investigation.

2.8. Purpose

The purpose of this thesis is to:

1. Evaluate the effect of wrist posture on enslaving, and accuracy, at 25% MVC during ramp contractions (ascending, static, and descending phases).
2. Evaluate the effect of rate of force production has on enslaving, and accuracy, at 25% MVC during ramp contractions (ascending, static, and descending phases).

2.9. Hypotheses

It is hypothesized that:

1. In wrist flexion, isometric extension force will produce higher enslaving than isometric flexion force.
2. In wrist extension, isometric flexion force will produce higher enslaving than isometric extension forces.
3. Enslaving will be higher at faster rates of force development.
4. Accuracy will be affected by rate of force development, specifically, error and correlation to the template will be higher with faster rates.
5. Of all 3 phases the descending phase will be the most difficult to control, which will be seen through, (a) The greatest total absolute enslaving. (b) The highest RMSE, with the target trace, across both fingers. (c) The greatest antagonist compartment activation.

CHAPTER 3 – METHODS

3.1. Participants

Twelve right-handed male volunteers, with no history of hand, arm, or shoulder disorders participated in this study (age, 24.25 ± 1.36 years; height, 176.93 ± 7.17 cm; weight, 82.56 ± 11.03 kg). Participants were also screened to exclude experienced musicians of more than 5 years experience, specifically with instruments involving complex individual finger movements. The McMaster research ethics board approved the study protocol, and all participants provided informed written consent.

3.2. Experimental Set-up

Participants were seated in an upright posture with their right elbow and wrist supported on a table. Seating height was adjusted to approximately 120° elbow flexion with 0° shoulder abduction. Fingers were placed in four adjustable padded metal rings each attached to a force transducer (MLP50, Transducer Techniques, Temecula, CA, USA) mounted on a vertical metal plate. Rings were secured around the middle phalanx of digits 2-5. A wrist and dorsal hand support was adjusted to prevent movement at the wrist and MCP joints, secure a mid-prone forearm, and ensure desired wrist posture (Figure 3.1).

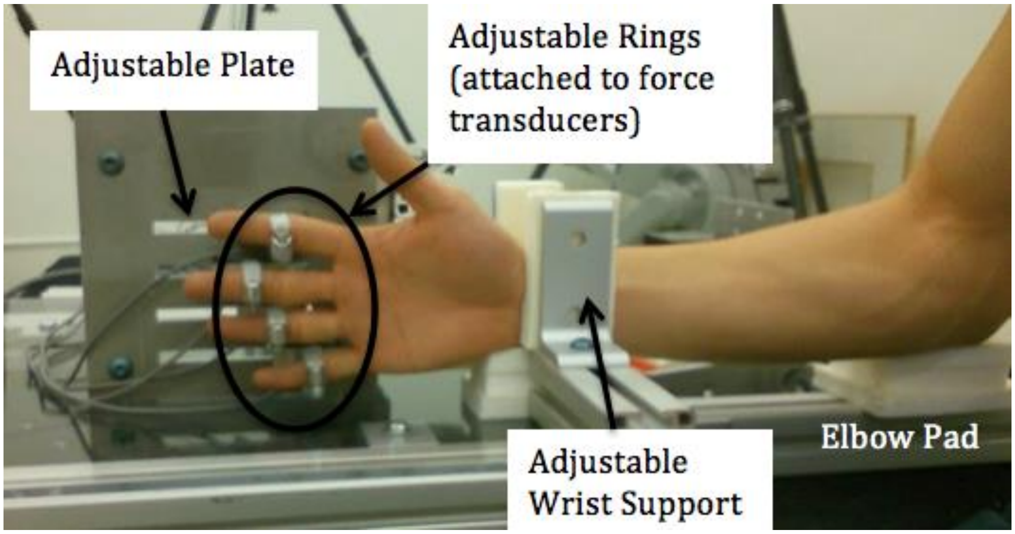


Figure 3.1. Experimental setup. Fingers were placed in adjustable metal rings attached to force transducers, which were set at 30° wrist flexion, 0° neutral wrist, and 30° wrist extension. Wrist and elbow were supported.

Surface EMG was collected using bipolar reusable surface electrodes with a fixed centre-to-centre electrode distance of 2 cm (SX230, Biometrics Ltd., Gwent, UK). The skin was always shaved and cleaned using alcohol wipes, and the electrodes were placed over the muscle belly along the fibre direction. Muscle activity was recorded from the four compartments of FDS (FDS2-5, corresponding to digits 2-5, starting from the index), and ED (ED2-5). Electrodes were placed according to Leijnse et al. (2008b), and Sanei and Keir (2013), with additional anatomical information from Shuenke et al. (2006) (Figure 3.2). For optimal electrode placement, ultrasound imaging was used during pilot testing to ensure proper orientation and placement along each muscle compartment. Placements were confirmed during testing with manual palpations and functional tests. All electrodes were placed with the wrist in a neutral (0°) posture and forearm mid-prone. A summary of electrode placements is presented in Table 3.1. The muscle belly of ED5 was not consistently distinguishable from extensor digiti minimi (EDM) and activity recorded with this electrode was likely a combination of both muscles (Leijnse et al., 2008a).

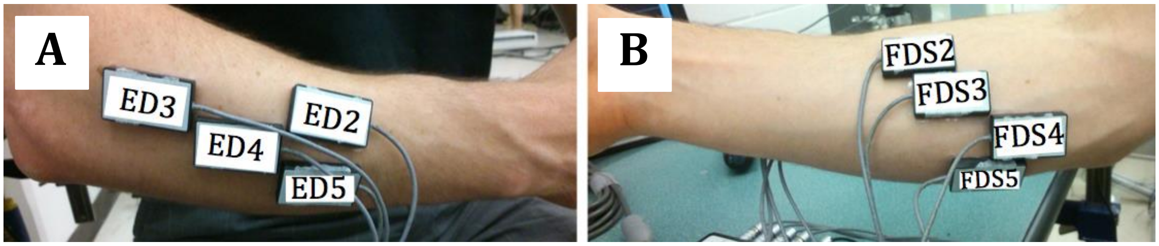


Figure 3.2. Electrode placements for the compartments of (A) ED, and (B) FDS.

Table 3.1. Electrode locations for the ED and FDS compartments. Adapted from Leijnse et al. (2008a), and Sanei and Keir (2013).

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

3.3. Experimental Conditions and Procedure

Participants performed a series of maximal voluntary contractions (MVC) in a neutral (0°) wrist posture. MVC trials were 5 seconds long with 1 minute rest between trials. Each trial was performed in both flexion and extension for all digits, and repeated twice (16 total MVCs). Participants were told the task finger to exert a force with, and in which direction. Additionally, participants were instructed to keep their fingers straight, and concentrate on exerting force with the task finger. If the peak forces differed by more than 5%, participants were asked to repeat the trial. The highest force, achieved during the MVC trials, was used as the maximal force (100% MVC). The highest peak of the processed EMG data obtained during the MVC trials, was averaged across the two accepted trials, and used as the maximal muscle activity for that compartment (100% maximum voluntary excitation, MVE).

Only the index and ring fingers were used as task fingers. The index and ring fingers were selected as the task fingers because they display the least and most enslaved forces, respectively, and therefore describe both ends of the enslaving spectrum (Slobounov et al., 2002b). For the index and ring fingers, participants performed a series of sub-maximal isometric contractions in both the flexion and extension directions, in each of three wrist postures: 30° wrist flexion, 0° (neutral), and 30° wrist extension (Figure 3.3). The wrist angle was defined as the angle between the ulna, and the dorsal aspect of the hand, with 0° being straight. Three trials were performed. The first trial consisted of three 5-second isotonic holds at 25% MVC, which were separated by 5 seconds rest. The second and third trials were isometric triangular (ramp) contractions at rates of 25% MVC/s (2 seconds) and 10% MVC/s (5 seconds) respectively. Participants increased force from rest to 50% MVC, maintained this force for 0.5 seconds, and then decreased to zero. Ramp contractions were repeated 3 times per trial, with five seconds rest between each ramp contraction. A summary of the trials performed for each finger is presented in table 3.2. A template was provided for visual feedback of all trials (Figure 3.4) and thirty seconds rest was given between trials. Participants were given time to familiarize and practice with each trace prior to collection. For all trials, participants were instructed to be as accurate to the trace as possible, and to not worry about the other non-task fingers. To avoid/minimize order effects, two Williams square designs were used. One was used to determine trial order within each wrist posture, and one to determine the order of wrist postures. Participants performed all trials within a single wrist posture before beginning trials in the other posture. In total, 12 trials were performed for each wrist posture (36 in total), excluding the initial MVC trials.

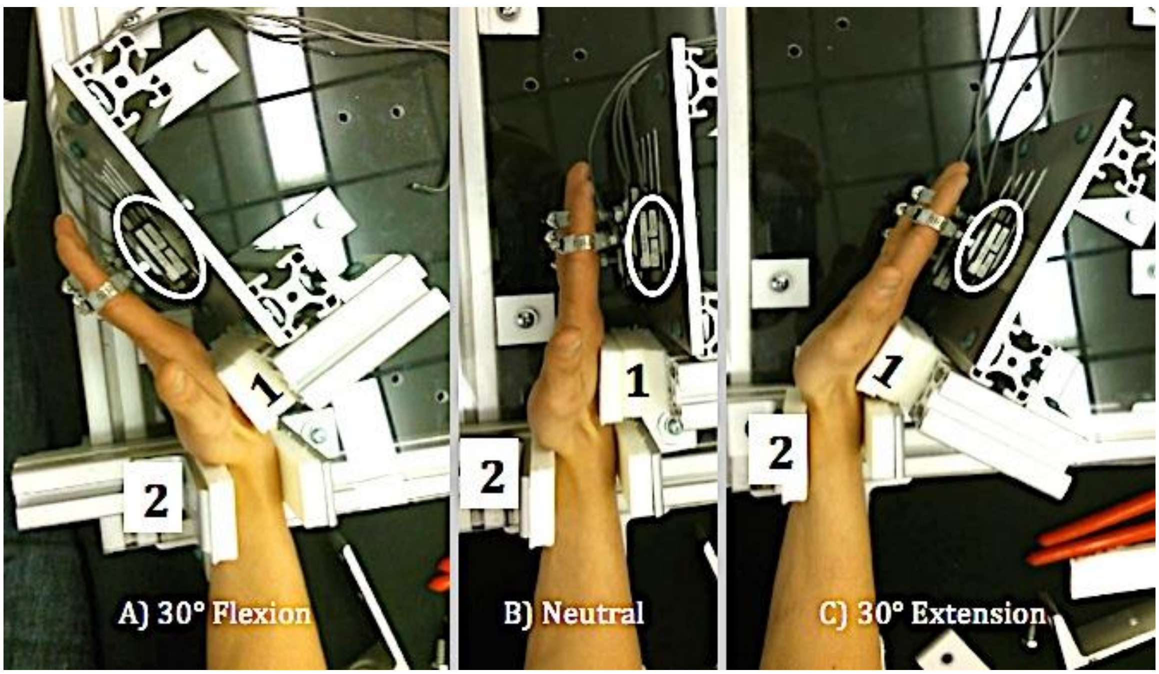


Figure 3.3. Top view of the apparatus securing the hand into: (A) 30° wrist flexion, (B) 0° neutral, and (C) 30° wrist extension. Force transducers were attached to padded rings and have been circled. Structure "1" is the adjustable dorsal hand support, and structure "2" is the adjustable wrist support.

Participants performed a relaxed trial prior to beginning the protocol for each wrist posture. During the trial, the participants' fingers were secured by the rings, but they did not actively exert a force for 5 seconds. These passive forces were recorded and removed, to ensure that at each wrist posture the force transducers read zero with no muscle activation.

Table 3.2. List of tasks performed by the index and ring fingers by all participants.

Wrist Posture	Flexion Contraction	Extension Contraction
30° Extended	Isotonic 25% MVC/s 10% MVC/s	Isotonic 25% MVC/s 10% MVC/s
0° Neutral	Isotonic 25% MVC/s 10% MVC/s	Isotonic 25% MVC/s 10% MVC/s
30° Flexion	Isotonic 25% MVC/s 10% MVC/s	Isotonic 25% MVC/s 10% MVC/s

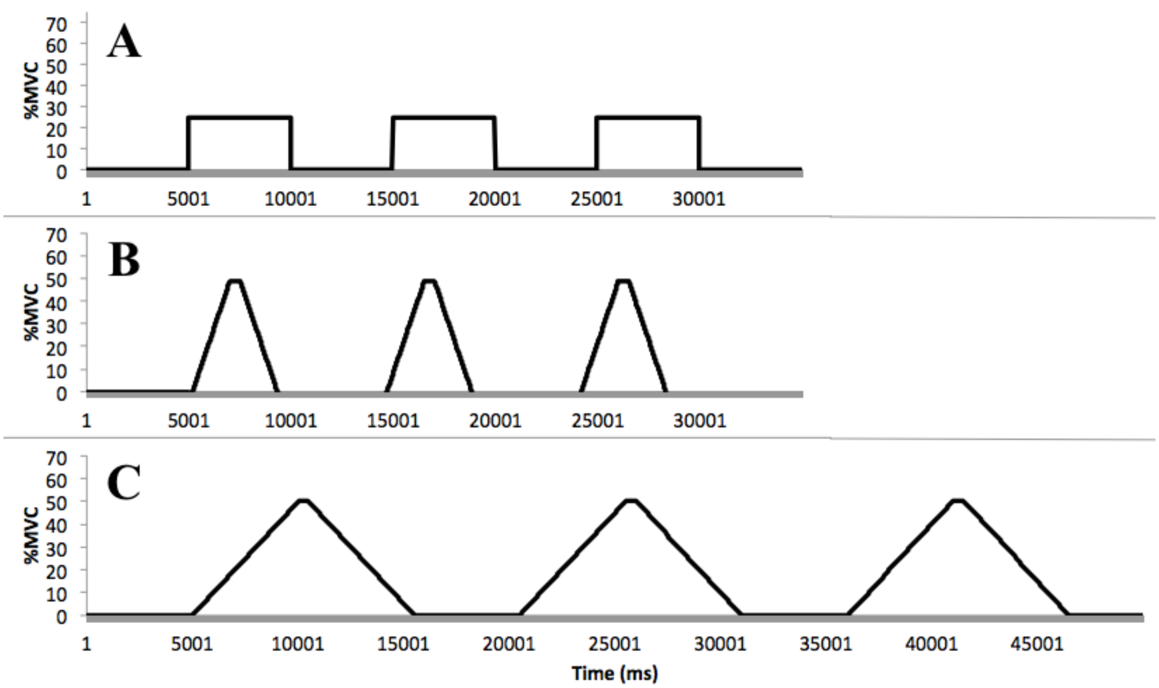


Figure 3.4. Schematic of the trace protocols: (A) Isotonic, (B) 2-second ramp, (C) 5-second ramp. Isotonic conditions consisted of a 5 second hold. Ramp trials increased at a rate of (B) 25% MVC/s, and (C) 10% MVC/s up to 50% MVC, a 0.5 second hold, and then decrease to zero over the same rate. Five seconds rest was given between exertions, and 30 seconds between consecutive trials.

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

3.4. Data Analysis

Raw EMG signals were full wave rectified and low pass filtered using a dual pass critically damped second order Butterworth filter with a cut off frequency of 3 Hz. After removing the initial bias and filtering, EMG from each compartment was normalized to the MVE of that compartment. Force signals were also low pass filtered using a second order dual pass critically damped Butterworth filter, with a 10 Hz cutoff frequency, and then normalized to the MVC for each finger.

For both EMG and force data, the mean of a 5 ms window about 25% MVC was analyzed. This window encompassed the target force of 25% MVC for the ascending and descending phase, and the middle 5 ms for the 25% MVC isotonic contraction. Since each ramp contraction was performed at two rates, five 25% MVC windows, termed "contraction conditions", were obtained for analysis. The 5 contraction conditions were: ascending 5 s (A5), ascending 2 s (A2), isotonic (ISO), descending 2 s (D2), and descending 5 s (D5). Where the 5 second conditions were from the 10% MVC/s trials, and the 2 second conditions from the 25% MVC/s trials. Note that ISO was collected from a separate trial. Force data were used to calculate the enslaving effect, which was defined as the force produced in each of the non-task fingers (slave fingers), normalized to the MVC of that particular slave finger.

Accuracy was assessed using root mean square error (RMSE) and Pearson Product Moment correlation. RMSE was normalized to the MVC of the task finger, and was performed to see how far participants deviated from the trace, while the correlation provided insight to the accuracy of the slope. Normalized RMSE (NRMSE) and Pearson Product Moment correlations were calculated from middle 80% of each ramp phase, and the middle 4 seconds of the isotonic phase. Both the NRMSE and correlations compared the finger force to the target trace. The beginning and end 10% of each phase were excluded to remove inconsistencies from force initiation and termination. For each trial, NRMSE was normalized to the MVC of the task finger in the appropriate direction. Each trial was made up of three consecutive exertions. The data from the three exertions were averaged for the trial, which were then used for statistical analysis.

Figure 3.5. Schematic of one exertion from each submaximal trial: (A) Isotonic, (B) 2 second ramp, (C) 5-second ramp. Highlighted areas signify the middle 80% of each phase, where error and correlation measures were performed.

3.5. Statistical Analysis

Unpaired 2-tailed t-tests were performed to test the differences between flexion and extension MVCs of each finger. The dependent measure of enslaving effect (EE) was assessed using a 3 (wrist posture) × 2 (direction of force) × 5 (contraction condition)

× 3 (slave finger) repeated measures analysis of variance (ANOVA) for each task finger. EMG was assessed using a 3 (wrist posture) × 5 (contraction condition) × 8 (compartment) repeated measures ANOVA for each task finger (index and ring) and each direction of force (flexion and extension). Additionally, the initial passive forces were analyzed for significant differences using a 3 (wrist posture) × 4 (finger) repeated measures ANOVA. For NRMSE, a 3 (wrist posture) × 2 (task finger) × 2 (direction) × 5 (contraction condition) repeated measures ANOVA was used to analyze differences in error between the different exertions and between fingers. The correlations were analyzed similarly, however the isotonic condition was a horizontal line and could not be correlated, and therefore was excluded. This yielded a 3 (wrist posture) × 2 (task finger) × 2 (direction) × 4 (contraction condition) repeated measures ANOVA to test for significant differences. A significance level of $p < 0.05$ was used for all statistics, and any significant effects were further examined using Tukey's HSD post-hoc analysis.

Finally, a cross-correlation analysis was performed to determine the relationship between the EMG within the extensor compartments of ED, and within the flexor compartments of FDS. The EMG data was first de-biased and full-wave rectified before being normalized to the autocorrelation at time-lag zero.

CHAPTER 4 - RESULTS

A summary of the maximal voluntary flexion and extension contractions (N), for all fingers is provided in Table 4.1. Flexion MVCs were significantly higher than for extension for all fingers ($p < 0.001$). The mean flexion MVCs were approximately 4 times larger than extension MVCs of the same finger.

Table 4.1. MVCs (N) for flexion and extension in all fingers (*Mean* ± *SD*, n=12). *Significantly different between flexion and extension exertions ($p < 0.05$).

	Index*	Middle*	Ring*	Little*
Flexion	44.2 ± 10.9	34.3 ± 6.0	24.8 ± 7.6	27.1 ± 7.7
Extension	13.8 ± 4.2	9.0 ± 2.5	6.9 ± 2.2	8.4 ± 2.5

There was a significant wrist posture × finger interaction ($F_{2.6, 28.1} = 3.953$, $p = 0.023$) on resting finger forces, as well as a main effect of wrist posture ($F_{2, 22} = 59.827$, $p < 0.001$). Force was significantly lower in a flexed posture than extended (Figure 4.1). In every finger the resting force in the extension posture was significantly higher than in a flexed wrist posture ($p < 0.05$).

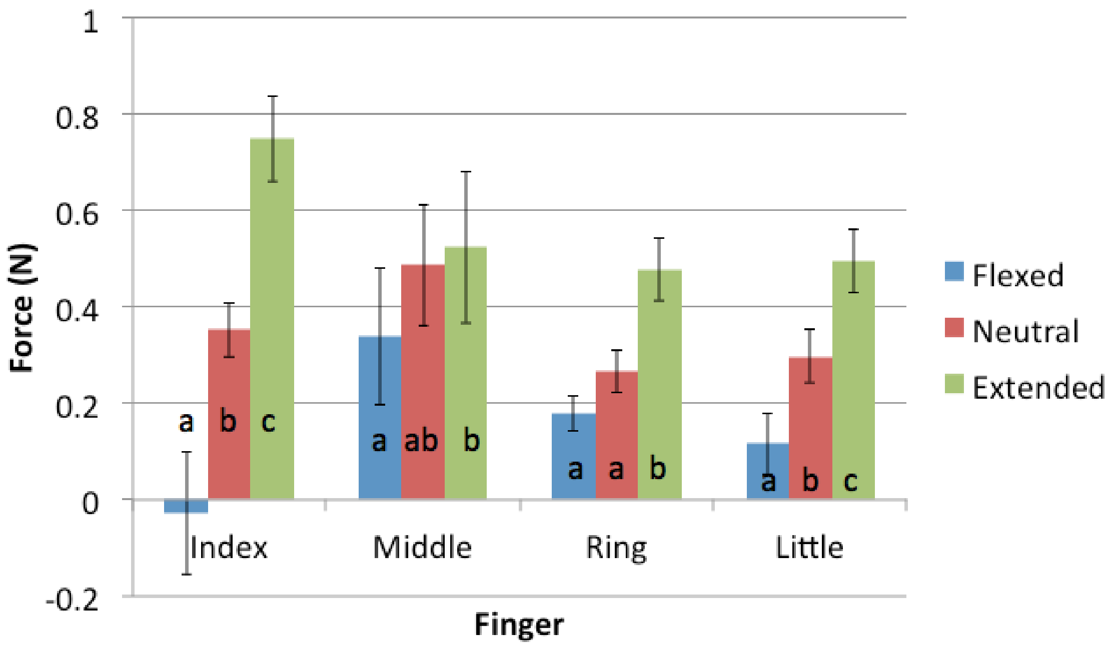


Figure 4.1. Relaxed finger force (N ± SEM) in each finger at 30° flexion, 0° (neutral), and 30° extension of the wrist. Different letters denote significant differences ($p < 0.05$) between wrist postures.

4.1. Effects of Wrist Posture on EE and EMG

During active trials, the enslaving effect (EE) was significantly higher in adjacent fingers than the non-adjacent fingers, and in trials where the ring was the task finger. There were significant three-way interactions (wrist posture × direction of force × slave finger) on EE for the index, and ring fingers (Index, $F_{4, 44} = 2.887$, $p = 0.033$; Ring, $F_{4, 44} = 2.637$, $p = 0.046$; see Appendix A for all ANOVA outputs) (Figure 4.2). During ring finger extension exertions, an extended wrist posture had significantly higher EE on digits 2 (5.36 ± 1.3% MVC), and 5 (13.93 ± 2.1% MVC). When the index finger performed extension exertions, the 3rd digit had significantly higher EE in wrist extension (enslaved force = 6.38 ± 1.0% MVC), than with a flexed or neutral wrist (3.57 ± 1.0% MVC, and 3.68 ± 0.8% MVC, respectively). During index finger flexion exertions, digit

4 was significantly more enslaved in a neutral wrist posture (-4.78 ± 1.0% MVC), than extended (-1.83 ± 1.5% MVC). There were no significant differences in EE between wrist postures, during ring finger flexion exertions, even though digit 5 expressed positive EE in a flexed wrist posture, but not with a neutral and extended posture.

For flexion exertions in both the index and ring fingers, there were fewer differences in EE between wrist postures. In these cases, the interaction between direction of force and slave finger was significant for both task fingers (Index, $F_{2,22} = 4.437$, $p < 0.05$; Ring, $F_{2,22} = 4.077$, $p < 0.05$). During index flexion exertions, digits 4 and 5, produced forces in the extension direction (-3.2 ± 1.1, and -1.5 ± 1.0% MVC, respectively), which both differed significantly from the positive EE of the middle finger. Significantly lower EEs from the middle finger were also present during ring finger flexion exertions in the 2nd, and 5th digits (-2.4 ± 1.0% MVC and -0.2 ± 1.7% MVC, respectively).

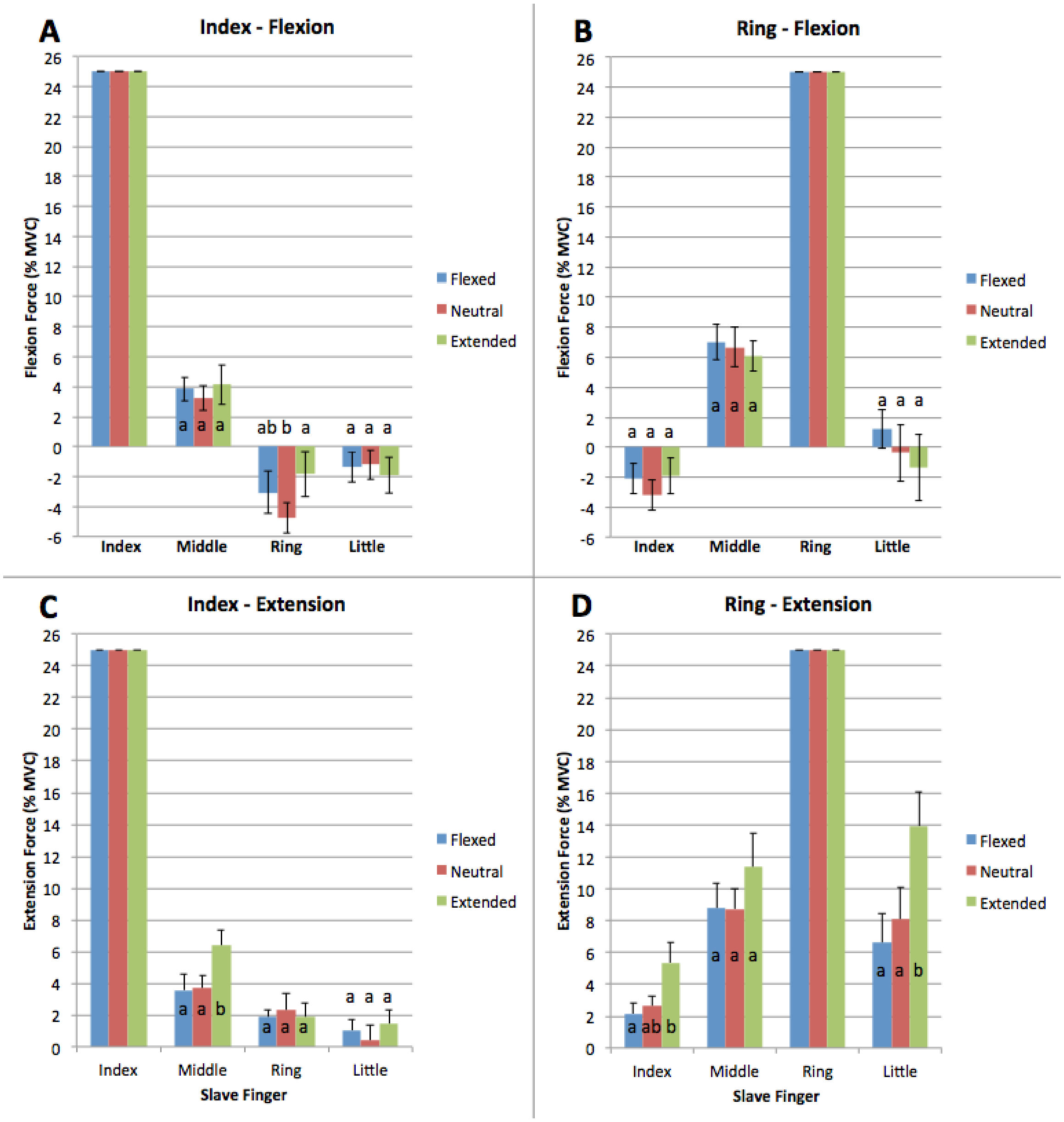


Figure 4.2. Force (% MVC ± SEM) during 30° flexion, 0° neutral, and 30° extension at the wrist, for index flexion exertions (A), ring flexion exertions (B), index extension exertions (C), ring extension exertions (D). There was a significant wrist posture × direction of force × slave finger interaction for both the index (A, C), and ring (B, D) finger. Different letters denote significant differences ($p < 0.05$) in EE between wrist postures for each finger.

For index finger flexion, index finger extension, and ring finger extension exertions, there was a significant 3-way interaction in each (wrist posture × contraction condition × compartment) on EMG ($F_{56, 616} > 1.7$, $p < 0.01$). The differences within this interaction were found in the agonist compartments, and had the same effect as the wrist posture × compartment, and contraction condition × compartment interactions. Therefore, the 2-way interactions will be presented.

There was a significant interaction effect (wrist posture × compartment) in the muscle activity level (%MVE) during, index extension exertions ($F_{14, 154} = 21.786$, $p < 0.0001$), ring flexion exertions ($F_{14, 154} = 3.918$, $p < 0.0001$), and ring extension exertions ($F_{14, 154} = 15.512$, $p < 0.0001$) (Figure 4.3). Index flexion exertions showed no significant differences in EMG, for the wrist posture × compartment interaction (Index flexion, $p > 0.05$). During extension exertions for the index and ring fingers, EMG of the extensor task compartments (ED2 and ED4, respectively) was significantly different between wrist postures. This showed significantly more muscle activity in the extensor task compartment with an extended wrist (30.1 ± 2.9 and 29.2 ± 2.8% MVE, in ED2 and ED4 respectively). Additionally, during extension exertions the extensor EMG of the slave fingers was significantly higher in the extension wrist posture, regardless of task finger. However, flexor EMG did not differ between wrist postures during extension exertions.

There was a significant wrist posture × compartment interaction in ring finger flexion exertions as well ($F_{14, 154} = 3.918$, $p < 0.0001$). However, EMG decreased in the task compartment (FDS4) with wrist extension. A flexed wrist posture yielded significantly more EMG than an extended posture in the task compartment (FDS4, 22.7 ± 1.8% MVE), and in the slave compartment FDS5 (21.5 ± 4.1% MVE), but not in the other flexor compartments (FDS2 and FDS3).

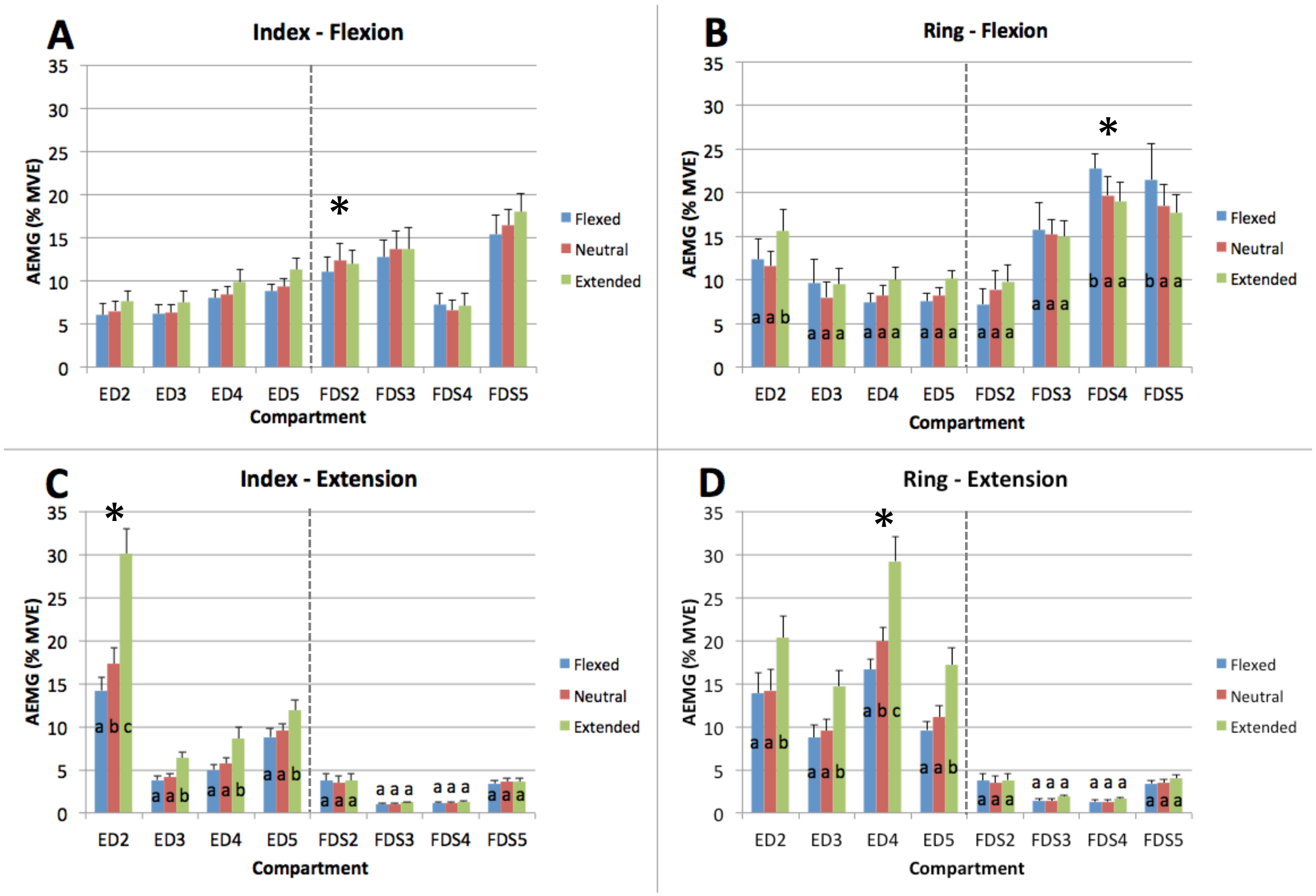


Figure 4.3. EMG (% MVE ± SEM) of all ED and FDS compartments for all 3 wrist postures in index flexion exertions (A), ring flexion exertions (B), index extension exertions (C), ring extension exertions (D). Index extension, ring flexion, and ring extension exertions had a significant wrist posture × compartment interaction ($p < 0.05$). *Denotes the task compartment for each exertion. Different letters denote significant differences ($p < 0.05$) in EMG between wrist postures. Index flexion exertions had no significant wrist posture × compartment interaction, but are presented for comparison.

4.2. Effects of Contraction Condition on EE and EMG

The three-way interaction involving the effect of contraction condition on EE (contraction condition × direction of force × slave finger) was not significant for either the index or ring fingers ($p > 0.05$). A significant two-way contraction condition × slave finger interaction existed for both the index ($F_{3.4,\ 37.1} = 5.904$, $p = 0.001$), and ring fingers ($F_{3.5,\ 38.5} = 6.429$, $p = 0.001$) (Figure 4.4). For these interactions, sphericity was violated and a Greenhouse-Geisser correction was used. Significant differences between contraction conditions were found in digits 3, and 5 during ring finger exertions, and in digit 3 for index finger exertions. In the 3rd and 5th digits during ring finger exertions, the highest EE was found in the D5 contraction condition (11.2 ± 1.6% MVC and 8.0 ± 1.7% MVC, respectively), which was significantly higher than the A5, A2, and isotonic contraction conditions ($p < 0.05$). Furthermore, the EE was significantly higher in the D2 contraction condition than the A2 contraction condition, in the 3rd and 5th digits during ring finger exertions. During index finger exertions, the D5 contraction condition (6.0 ± 0.7% MVC) had significantly more EE in the 3rd digit, than the A5, and A2 contraction conditions. Additionally, during index exertions, there was a significant difference in EE on the 4th digit between the isotonic, and D2 contraction conditions. The isotonic contraction condition had a very small EE in the 4th digit (0.3 ± 0.5% MVC), but the D2 contraction condition yielded enslaved forces in the negative direction (-1.9 ± 1.0% MVC).

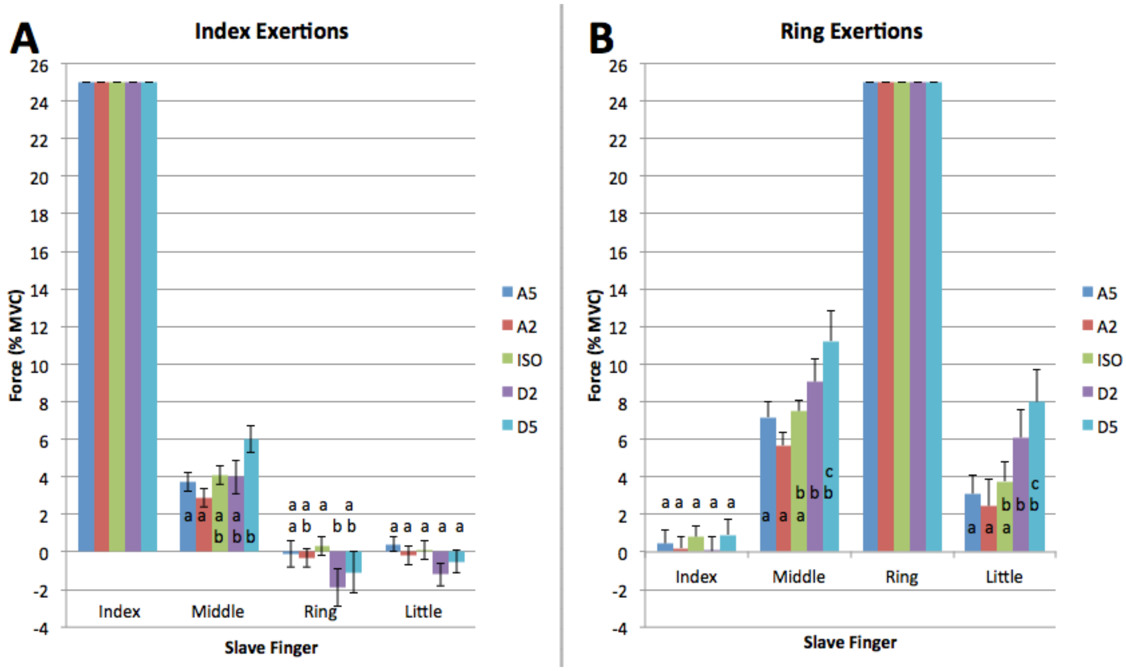


Figure 4.4. Force (% MVC ± SEM) during A5, A2, ISO, D2, and D5 contraction conditions, for index exertions (A), and ring exertions (B). There was a significant contraction condition × slave finger interaction for both the index (A), and ring (B) finger. Different letters denote significant differences ($p < 0.05$) in EE between contraction conditions for each finger.

4.2.1. Muscle Activity of the Task Compartment

There was a significant interaction of contraction condition × compartment in the EMG for index finger flexion, index finger extension, ring finger flexion, and ring finger extension exertions (Index and ring flexion, $F_{28, 308} > 5.06$, $p < 0.0001$; Index and ring extension, $F_{28, 308} > 6.65$, $p < 0.00001$). For index extension, ring flexion, and ring extension exertions, Tukey's HSD test revealed that the A2 and A5 contraction conditions of the task compartment had significantly higher muscle activation than all the other contraction conditions ($p < 0.05$; Figure 4.5). For index extension, and ring extension exertions, the task compartment EMG (ED2 and ED4, respectively) during the

A2 contraction condition was significantly higher than the A5 ($p < 0.05$). In index extension and ring flexion exertions, the EMG of the task compartment (ED2 and FDS4, respectively) was significantly lower during the D2 and D5 conditions than the other conditions ($p < 0.05$). However, in ring finger extension contractions, ED4 activity in the D5 condition (20.8 ± 1.8% MVC) was not significantly different from the isotonic activity (20.5 ± 1.7% MVC). Both the ring finger extension D5 and isotonic conditions had significantly higher ED4 activity than the D2 condition (17.3 ± 1.3% MVC) ($p < 0.05$). In index flexion exertions, FDS2 activity levels were not significantly different throughout conditions, with the exception that the A5 condition (12.9 ± 1.9% MVC), was significantly higher than the D2 condition (10.2 ± 1.5% MVC).

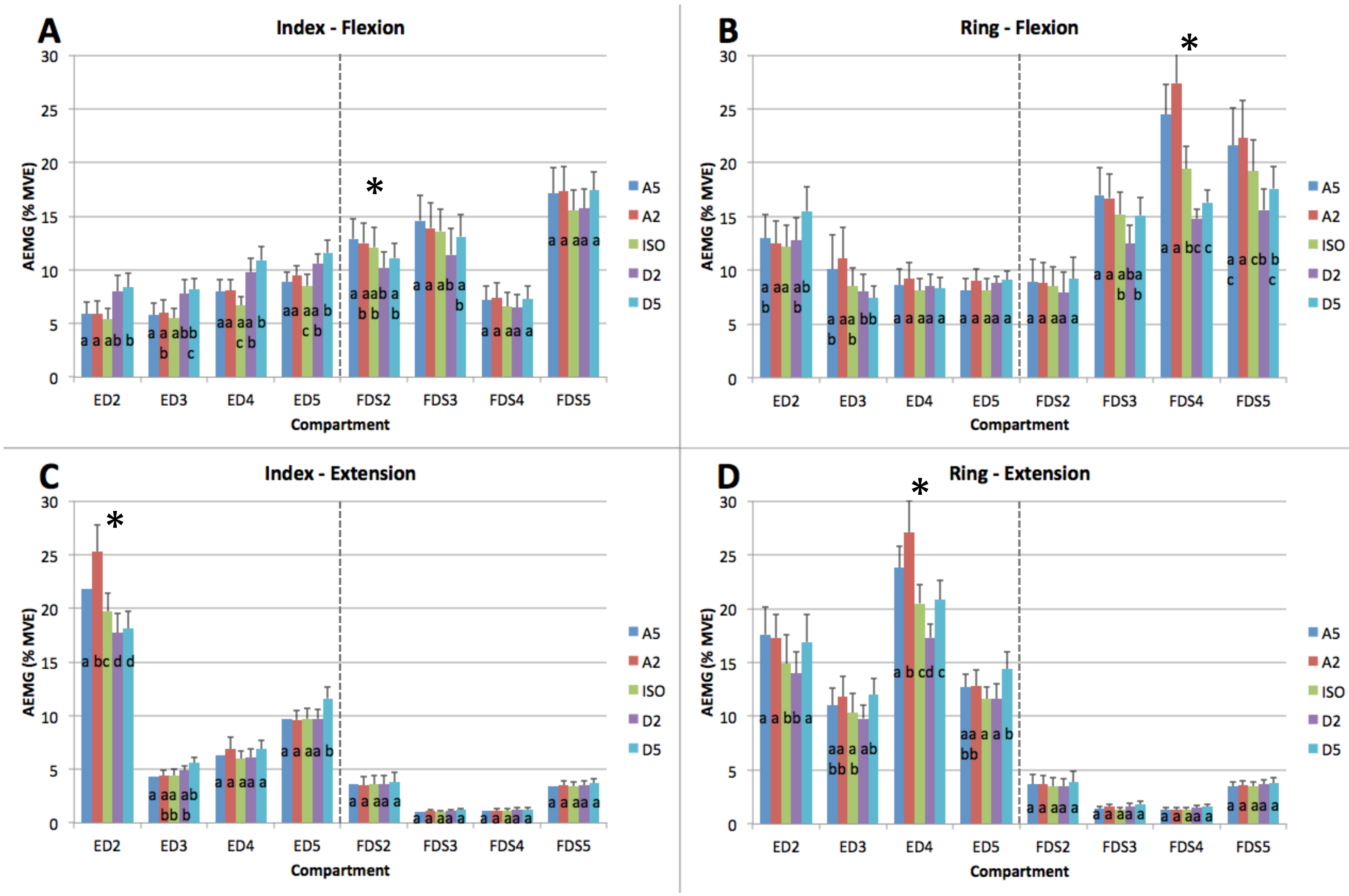


Figure 4.5. EMG (% MVE ± SEM) of all ED and FDS compartments for all 5 contraction conditions in exertions of (A) index flexion, (B) ring flexion, (C) index extension, (D) ring extension. There was a significant contraction condition × compartment interaction in A, B, C, and D. *Denotes the task compartment for each exertion. Different letters denote significant differences ($p < 0.05$) in EMG between contraction conditions.

4.2.2. Muscle Activity of the Agonist Compartments

Within the significant contraction condition × compartment interaction differences in muscle activity between contraction conditions of the agonist compartments were present (Index and ring flexion, $F_{28, 308} > 5.06$, $p < 0.0001$; Index and ring extension, $F_{28, 308} > 6.65$, $p < 0.00001$). Tukey's HSD test found the agonist (extensor) compartments during ring finger extension had significantly higher muscle activity in the D5 condition, than the D2. Additionally, the A2 and A5 conditions were significantly higher than the D2 condition in FDS3, as well as the D2 and D5 condition in FDS5, for ring flexion exertions ($p < 0.05$). During these exertions, the muscle activity in the FDS5 was significantly higher in the A2 condition than the isotonic, which was significantly higher than the D2 condition. The agonist compartments, ED3 and ED5, showed significantly higher muscle activity in the D5 condition than the A5, during index extension exertions. The only significant difference in agonist EMG for index flexion exertions was in the FDS3 compartment, where the D2 condition expressed significantly lower muscle activity than A2, A5, and isotonic conditions.

4.2.3. Muscle Activity of the Antagonist Compartments

Differences in muscle activity between contraction conditions of the antagonist compartments were also present for the significant contraction condition × compartment interaction (Index and ring flexion, $F_{28, 308} > 5.06$, $p < 0.0001$; Index and ring extension, $F_{28, 308} > 6.65$, $p < 0.00001$). Tukey's HSD test revealed that the antagonist (flexor) activation for all extension exertions was not significantly different between the contraction conditions ($p > 0.05$). With index finger flexion exertions, D5 had significantly higher muscle activity in all extensor compartments, than the A5 condition

($p < 0.05$). During index flexion exertions, the ED4 and ED5 compartments had significantly higher muscle activity during D2 and D5 conditions, than the isotonic condition, which was not significantly different than the A2 and A5 condition ($p < 0.05$). During the same exertions, Tukey's HSD test showed muscle activity in ED3 was significantly lower in the A2 condition than the D5, but not the D2 condition ($p < 0.05$).

4.3. Effects of Wrist Posture and Contraction Condition on Accuracy

There was a significant wrist posture × direction of force interaction on NRMSE ($F_{2, 22} = 7.890$, $p = 0.003$; Figure 4.6a). In extension exertions, NRMSE was significantly higher than flexion exertions with a neutral and extended wrist ($p < 0.05$). NRMSE was highest with extension exertions, and an extended wrist, which was significantly higher than extension exertions with a flexed wrist, but not with a neutral wrist posture. There was a main effect of direction on NRMSE as extension exertions had significantly higher error than flexion exertions (flexion force = 3.0 ± 0.2, extension force = 4.6 ± 0.5; $F_{1, 11} = 13.206$, $p < 0.01$). There were no significant differences in NRMSE between wrist postures with flexion exertions.

There was also a main effect of contraction condition on NRMSE ($F_{4, 44} = 40.795$, $p < 0.001$; Figure 4.6b). Significant differences were found between isotonic, 10% MVC/s, and 25% MVC/s rates. Isotonic conditions yielded the least error, whereas the 25% MVC/s (A2 and D2) rates yielded the highest. The main effect of task finger was not significant ($p = 0.258$)

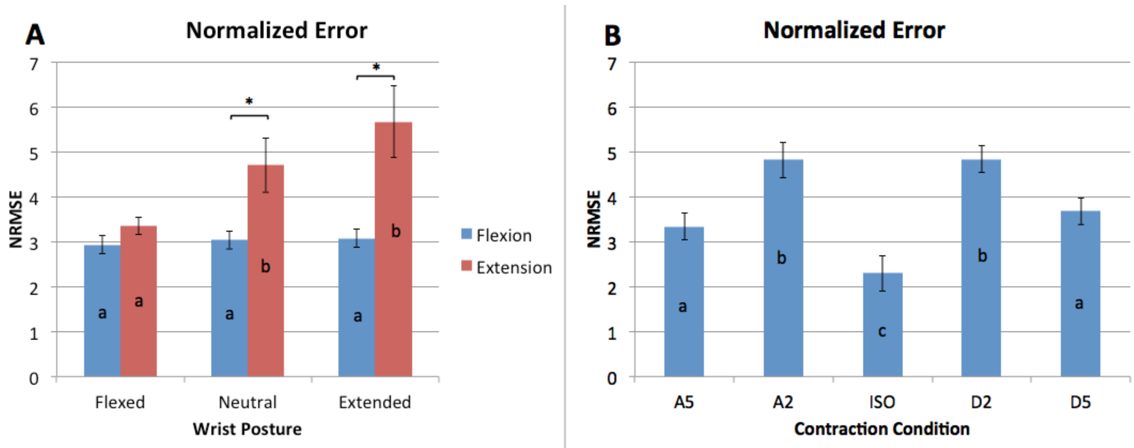


Figure 4.6. Participant error (NRMSE ± SEM) normalized to the MVC of the active finger. Error was measured as differences from the target trace. (A) Significant wrist posture × direction of force interaction, (B) Significant main effect of contraction condition on NRMSE. Different letters denote significant differences ($p < 0.05$) in NRMSE between wrist postures (A), and conditions (B). *Significant difference ($p < 0.05$) between directions of force.

The Pearson product moment correlations for the ramp phase were very high for all conditions ($r > 0.95 \pm 0.023$), and wrist posture had no significant effect on the correlations. The 5-second conditions (A5 and D5) were more highly correlated with the trace than the 2-second conditions (A2 and D2) (main effect of contraction condition, $F_{3, 33} = 6.997$, $p < 0.01$). There was a main effect of direction of force ($F_{1, 11} = 20.833$, $p < 0.01$), as well as task finger ($F_{1, 11} = 7.602$, $p < 0.05$), where flexion forces and the index finger yielded greater correlations.

CHAPTER 5 - DISCUSSION

Our results support previous findings that the ring finger was the least independent, and the adjacent fingers were the most enslaved (Zatsiorsky et al., 2000; Slobounov et al., 2002a; Kim et al., 2008; Sanei and Keir, 2013; Wilhelm et al., 2014). By varying wrist posture we were able to alter the length of the muscle and analyze its effects on enslaving. However, instead of affecting the EE via differences in passive tension through mechanical restrictions, neural changes from different muscle lengths, and absolute force, appeared to have a greater effect.

There was considerable variation seen in the EE across wrist posture, contraction condition, direction of force, and slave finger. Wrist posture had the greatest impact on EE in extension exertions, which was more pronounced in the ring finger. Contrary to our hypothesis, there was significantly more EE in extension exertions with a shorter muscle length found in wrist extension (Figure 4.2). In this posture, mechanical connections, such as the juncture tendinei, should be in a less taut state, suggesting that the increased enslaving effect may be attributed to a neural component. A similar trend of higher EE with a shorter muscle length was present in the adjacent fingers during ring finger flexion exertions. Unlike the extensors, this finding was not significant, and may be more pronounced at extreme muscle lengths. The current protocol used wrist angles of 30° which represents 43% of the reported range of motion for the wrist of 70° flexion to 76° extension, with the metacarpophalangeal joint ranging from 90° flexion to 20° extension (Mallon et al., 1991; Stubbs et al., 1993). However, the straight metacarpophalangeal joint was biased towards the extensor side of the range of motion, suggesting that the postures tested in this thesis had extensor muscle lengths shorter than they would be with a neutral metacarpophalangeal angle (approximately 45° flexion). This may explain why the EE was more pronounced with extension exertions.

Muscle activity can help describe the differences seen in the EE between wrist postures. During extension exertions, EMG was significantly higher in all extensor compartments in wrist extension (Figure 4.3). Similarly for ring finger flexion exertions, the EMG was significantly higher with the wrist flexed for both FDS4 and FDS5 (22.7 ± 1.8, and 21.5 ± 4.1 respectively). This change in EMG between wrist postures supports previous findings, that more muscle activity is required to achieve the same force, at shorter muscle lengths (Rack and Westbury, 1969; Heckathorne et al., 1981; Vander Linden et al., 1991). However, the muscle activities of the extensor slave fingers were also higher at shorter lengths. This suggests that the extensors are, to some extent, controlled by a common drive (De Luca and Erim, 1994). This might explain why the EE was typically higher with an extended wrist during ring finger extension exertions. The same was only found in the 3rd digit during index extension exertions, likely because of the added control from the extensor indicis (EI). The EI would have a more independent neural activation from the compartments of ED, which would suggest less neural drive to the compartments of ED during index finger exertions, than ring finger exertions. This can be seen by the lower increase in muscle activity of the extensors, with an extended wrist, during extension exertions of the index finger (Figure 4.2).

In extension exertions, NRMSE was significantly lower with a flexed wrist, than neutral or extended ($p < 0.05$). However, there were no differences across wrist posture in flexion exertions. Furthermore, there was a main effect of NRMSE to be significantly higher in extension than flexion ($p < 0.01$). The greater errors, and EEs seen with extension exertions, indicate that they are more difficult to control. On the other hand, during flexion exertions there were no changes in EE or error with wrist posture, suggesting that the control of the fingers during flexion exertions is unaffected by wrist posture. I suggest that error and EE act together in flexion and extension exertions, and are affected similarly to changes in wrist posture.

During index flexion exertions, negative forces were present in non-task fingers. This negative, or extension force, was not enslaved force, but instead a force artifact due to the moment created about the long axis of the hand. The extension forces by the 4^{th} and 5^{th} digits aided the moment acting to produce force in the index finger. This suggests that during index flexion exertions, participants may have attempted to rotate their hand through the metacarpals to follow the template. Sanei and Keir (2013) reduced these rotational effects using a splint around the 4^{th} and 5^{th} metacarpals, and did not experience sizeable extension force during index flexion tasks. However, like Sanei and Keir (2013), the current study found all positive (enslaved) forces during extension exertions suggesting that rotational control was not a factor, likely because of the lower absolute forces. During ring flexion exertions, our EE values were similar to Sanei and Keir (2013), including the extension force artifact seen in the index finger.

Our hypothesis that the descending phase would be more difficult to control, and would be seen through greater antagonist activation was confirmed, in one (index flexion) of the four exertions (index flexion, index extension, ring flexion, ring extension). During index flexion, all extension compartments expressed significantly higher muscle activity in the D5 condition, than the A5 (Figure 4.5). There were no significant differences in the antagonist EMG during extension exertions. The difference in muscle activity between contraction conditions during index flexion tasks may be due to the difficultly in controlling during the descending phases.

Similarly, our hypothesis that the descending phase would express greater EE was also confirmed for the adjacent fingers. During ring finger contractions, the descending phase (D2 and D5) had significantly more enslaved force in the 3^{rd} and 5^{th} digits, than the ascending phase of the same rate (A2 and A5). In index finger exertions, the EE was significantly higher during the D5 condition, than the A5 condition on the 3^{rd} digit. Within these compartments there was no clear relation between agonist muscle activity in the A5 and D5 contraction conditions, and in the EE for the same conditions. The difference in enslaving cannot be attributed to antagonist activation either, because in most compartments antagonist activation did not change with contraction condition. In the few compartments where significant differences were observed (between D5 and A5), antagonist muscle activity was higher in the descending phase, which would seem to contradict the increased EE. Our results show that the adjacent slave compartments produce greater enslaved force during the D5 condition than the A5 condition, which appear to be independent of compartment muscle activity. This suggests that mechanical linkages may effect the enslaving seen between contraction conditions. However, since the wrist posture did not affect the EE as predicted from increased tension in the intertendinous connections, these linkages must be occurring elsewhere.

Lower muscle activity was needed to produce the same force in the descending phase versus the ascending phase in the task compartment. The differences in muscle activity might be due to differences within the muscle filaments themselves (Joyce and Hack, 1969), as well as motor unit recruitment and rate coding between phases

(Henneman et al., 1957). During the descending phase, the actin and myosin filaments are releasing from one and other. However, intact linkages that have not released would passively resist lengthening, thus increasing force (Joyce and Rack, 1969). Additionally, motor units decruit at a lower discharge rate than they recruit, lowering the observed muscle activity (Milner-Brown et al., 1973; De Luca et al., 1982; Oya et al., 2009). Both these factors would combine to produce the same amount of force, with lower muscle activation, which is seen in descending contraction conditions.

Unexpectedly, the rate of force development had a larger effect on NRMSE than did the ascending or descending phase. The descending phase had the largest EEs, and was expected to have the greatest error. However, in all cases, the highest error was associated with the fastest rates (A2 and D2), and the lowest with the isotonic trial. Clearly the rate of force development was the determining factor for error, whereas for the EE the phase (and to a smaller extent, the rate as well) was the determining factor. It appears that there is some sort of trade off between the EE, and error, across contraction conditions. Where faster contractions yield less enslaved forces, but greater error (Kim et al., 2008). Significant differences were present in the NRMSE between the two rates, and the isotonic phase ($p < 0.05$). The 2-second trial was very fast and left participants little time to adjust and compensate to be more accurate, thus yielding greater error. Also, it is believed that the faster rate of the D2 condition was quick enough that participants made a decision to release force, and committed, thus decreasing EE. Whereas the 5-second trial and isotonic trials were longer phases (5-seconds each) and allowed participants more time to constantly control and adjust force, thus reducing error and increasing EE. Despite consistently greater EE in the D5 contraction condition than D2, differences were not statistically significant.

At the target force of 25% MVC, there were great differences in muscle activity of the task compartment between contraction conditions. In all exertions, except index finger flexion, the A2 condition had significantly more task compartment activity than all other conditions. Additionally, ascending phases of the task compartment had significantly more activity than the descending phases ($p < 0.05$). It is believed the A2 condition had more muscle activity because it was the fastest phase with increasing force. Milner-Brown et al. (1973) found that with faster triangular waveforms, motor units were recruited earlier and with a faster firing rate in the ascending, but not the descending phase. This may be a mechanism the body uses to prepare for a quick increase in force, and could explain the increase in EMG during the A2 condition.

The antagonist muscle activation was always higher during flexion exertions, than extension. This is likely due to the instruction participants received to keep their fingers straight while exerting the force. During flexion exertions, finger extensor force is necessary to maintain a straight distal interphalangeal joint. This was then seen through higher antagonist ED compartment activation.

Passive tension was a factor in the forces expressed, and increased as the wrist was extended (Figure 3.4). However, it appears that the absolute force of the exertions had a much larger effect on the EE than the passive forces. The flexion MVCs for each finger were approximately four times greater than the extension forces (Table 4.1), similar to Lieber et al.'s (1992) predicted forces based on muscle architecture. This, plus the extension forces in the 4^{th} and 5^{th} digit, suggest that a larger moment about the long axis of the hand that was present during index flexion exertions, but not in extension exertions. The EE has been reported to reduce this moment by Zatsiorsky et al. (2000), but their apparatus did not measure forces in the extension direction. If the EE does reduce this moment during flexion exertions, our results suggest it was not enough to completely negate the moment.

Forces in the opposite direction of the task have rarely been reported in finger independence studies. Most studies have used an apparatus consisting of either finger loops attached to force transducers, or piezoelectric sensors that measure only one direction (Zatsiorsky et al., 1998, 2000; Slobounov et al., 2002a, b; Kim et al., 2008; Martin et al., 2009; Wilhelm et al., 2014). This study shows that even small forces (25% MVC) can elicit a moment about the long axis of the hand, which involves forces in the opposite direction from the non-task fingers. Future studies must use force transducers that measure in tension and compression, to accurately evaluate the EE.

5.1 Limitations

There are a few limitations to the present study. First, the hand postures were slightly biased towards the extended side of the range of motion, due to the fixed metacarpophalangeal joint. This caused almost all the passive forces to be exerted in the flexion direction, and the effects of the force length relationship to be mainly expressed in extension exertions. Also, the participants created a moment about the long axis of the hand during index flexion exertions that involved extension forces in the 4th and 5th digits. This may have resulted in our EE values for the ring and little fingers to be underestimated. A wrist support and dorsal hand brace was used to reduce this rotation, however this rotation appeared to occur more distally. Sanei and Keir (2013) used a splint on the 4th and 5th metacarpals to reduce hand rotation, however due to our changing wrist posture this was not possible. The use of surface electrodes often generates concern of crosstalk. To minimize this effect we followed guidelines by Leijnse et al. (2008b), and Sanei and Keir (2013) for electrode placement. Additionally, ultrasound was used in pilot testing to confirm compartment location. This allowed for accurate electrode placement, which was confirmed with functional testing. Mogk and Keir (2003) also concluded that there should be minimal crosstalk with well-placed electrodes on the flexor and extensor sides of the forearm.

5.2 Conclusions

For the enslaving effect, both wrist posture and contraction condition were found to have a significant interaction with direction of force and slave finger. These findings were more pronounced in the fingers adjacent to the task finger, and in extension exertions. Increased muscle activity was found in the slave compartments at shorter lengths during extension exertions, supporting a theory of common neural drive. Additionally, participants exhibited greater error in extension exertions which was also highest at shorter muscle lengths, suggesting greater difficulty in control resulting in greater enslaving between fingers. Changes in enslaving effect were found almost exclusively in extension exertions, which supports previous work that the flexors are more independent than the extensors.

Differences in enslaving between contraction conditions emerged in fingers adjacent to the task finger and were independent of wrist posture. While the enslaving effect was influenced by contraction condition, this appeared to be independent of muscle activity, suggesting the potential for mechanical linkages within the compartments. Errors in tracing the target force appeared to be influenced by the rate of the contraction, whereas muscle activity of the task compartment was impacted more by the type of exertion (i.e. ascending, isotonic, or descending).

This thesis found new evidence to better understand the control of the fingers by altering wrist posture and the type of contraction. These control issues play a role in everyday life and may be used in rehabilitation strategies, work design and further our knowledge of the complex relationship between neural and mechanical control of the hand and fingers.

CHAPTER 6 - REFERENCES

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APPENDIX A. Statistics – ANOVA Tables

For all ANOVA tables, Greenhouse-Geisser values have been supplied when Mauchly's test of Sphericity was significant.

Enslaving Effect

INDEX					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Wrist Posture	0.022	2.000	0.011	3.683	0.042
Direction of Force	0.217	1.000	0.217	10.174	0.009
Condition Contraction	0.023	2.340	0.010	3.903	0.028
Slave Finger	0.504	2.000	0.252	35.614	0.000
Wrist Posture x Direction of Force	0.003	2.000	0.002	0.184	0.833
Wrist Posture x Condition Contraction	0.012	3.538	0.003	1.845	0.147
Direction of Force x Condition Contraction	0.031	4.000	0.008	5.304	0.001
Wrist Posture x Direction of Force x Condition Contraction	0.013	3.991	0.003	2.549	0.053
Wrist Posture x Slave Finger	0.011	4.000	0.003	2.355	0.068
Direction of Force x Slave Finger	0.090	2.000	0.045	4.437	0.024
Wrist Posture x Direction of Force x Slave Finger	0.029	4.000	0.007	2.887	0.033
Condition Contraction x Slave Finger	0.048	3.378	0.014	5.904	0.001
Wrist Posture x Condition Contraction x Slave Finger	0.009	16.000	0.001	1.455	0.122
Direction of Force x Condition Contraction x Slave Finger	0.011	3.312	0.003	1.560	0.213
Wrist Posture x Direction of Force x Condition Contraction x Slave Finger	0.007	16.000	0.000	1.002	0.457
Error					
Wrist Posture	0.065	22.000	0.003		
Direction of Force	0.235	11.000	0.021		
Condition Contraction	0.064	25.736	0.002		
Slave Finger	0.156	22.000	0.007		
Wrist Posture x Direction of Force	0.192	22.000	0.009		
Wrist Posture x Condition Contraction	0.070	38.914	0.002		
Direction of Force x Condition Contraction	0.064	44.000	0.001		
Wrist Posture x Direction of Force x Condition Contraction	0.054	43.905	0.001		
Wrist Posture x Slave Finger	0.051	44.000	0.001		
Direction of Force x Slave Finger	0.223	22.000	0.010		
Wrist Posture x Direction of Force x Slave Finger	0.112	44.000	0.003		
Condition Contraction x Slave Finger	0.090	37.156	0.002		
Wrist Posture x Condition Contraction x Slave Finger	0.070	176.000	0.000		
Direction of Force x Condition Contraction x Slave Finger	0.074	36.429	0.002		
Wrist Posture x Direction of Force x Condition Contraction x Slave Finger	0.075	176.000	0.000		

RING					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Wrist Posture	0.072	2.000	0.036	5.906	0.009
Direction of Force	1.033	1.000	1.033	22.460	0.001
Condition Contraction	0.199	1.421	0.140	11.249	0.002
Slave Finger	1.055	2.000	0.528	29.126	0.000
Wrist Posture x Direction of Force	0.143	2.000	0.072	13.695	0.000
Wrist Posture x Condition Contraction	0.007	3.578	0.002	0.938	0.444
Direction of Force x Condition Contraction	0.011	2.218	0.005	1.014	0.385
Wrist Posture x Direction of Force x Condition Contraction	0.005	8.000	0.001	0.948	0.482
Wrist Posture x Slave Finger	0.009	4.000	0.002	0.618	0.652
Direction of Force x Slave Finger	0.204	2.000	0.102	4.077	0.031
Wrist Posture x Direction of Force x Slave Finger	0.048	4.000	0.012	2.637	0.046
Condition Contraction x Slave Finger	0.086	3.503	0.025	6.429	0.001
Wrist Posture x Condition Contraction x Slave Finger	0.007	16.000	0.000	0.687	0.805
Direction of Force x Condition Contraction x Slave Finger	0.006	3.624	0.002	0.462	0.745
Wrist Posture x Direction of Force x Condition Contraction x Slave Finger	0.014	16.000	0.001	1.185	0.284
Error					
Wrist Posture	0.134	22.000	0.006		
Direction of Force	0.506	11.000	0.046		
Condition Contraction	0.195	15.631	0.012		
Slave Finger	0.399	22.000	0.018		
Wrist Posture x Direction of Force	0.115	22.000	0.005		
Wrist Posture x Condition Contraction	0.080	39.362	0.002		
Direction of Force x Condition Contraction	0.115	24.395	0.005		
Wrist Posture x Direction of Force x Condition Contraction	0.054	88.000	0.001		
Wrist Posture x Slave Finger	0.164	44.000	0.004		
Direction of Force x Slave Finger	0.549	22.000	0.025		
Wrist Posture x Direction of Force x Slave Finger	0.199	44.000	0.005		
Condition Contraction x Slave Finger	0.148	38.537	0.004		
Wrist Posture x Condition Contraction x Slave Finger	0.118	176.000	0.001		
Direction of Force x Condition Contraction x Slave Finger	0.139	39.867	0.003		
Wrist Posture x Direction of Force x Condition Contraction x Slave Finger	0.128	176.000	0.001		

EMG

INDEX FLEXION					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Wrist Posture	0.051	2.000	0.026	6.015	0.008
Condition Contraction	0.046	4.000	0.011	3.758	0.010
Compartment	1.623	7.000	0.232	7.222	0.000
Wrist Posture x Condition Contraction	0.009	3.826	0.002	0.812	0.520
Wrist Posture x Compartment	0.025	14.000	0.002	0.911	0.549
Condition Contraction x Compartment	0.121	28.000	0.004	5.063	0.000
Wrist Posture x Condition Contraction x Compartment	0.034	56.000	0.001	1.719	0.001
Error					
Wrist Posture	0.094	22.000	0.004		
Condition Contraction	0.133	44.000	0.003		
Compartment	2.472	77.000	0.032		
Wrist Posture x Condition Contraction	0.121	42.085	0.003		
Wrist Posture x Compartment	0.306	154.000	0.002		
Condition Contraction x Compartment	0.262	308.000	0.001		
Wrist Posture x Condition Contraction x Compartment	0.217	616.000	0.000		

INDEX EXTENSION					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Wrist Posture	0.281	1.162	0.242	33.942	0.000
Condition Contraction	0.015	1.721	0.009	5.255	0.019
Compartment	5.172	2.213	2.337	64.606	0.000
Wrist Posture x Condition Contraction	0.023	2.819	0.008	4.914	0.007
Wrist Posture x Compartment	0.675	14.000	0.048	21.786	0.000
Condition Contraction x Compartment	0.143	28.000	0.005	13.535	0.000
Wrist Posture x Condition Contraction x Compartment	0.138	56.000	0.002	7.959	0.000
Error					
Wrist Posture	0.091	12.786	0.007		
Condition Contraction	0.032	18.936	0.002		
Compartment	0.881	24.340	0.036		
Wrist Posture x Condition Contraction	0.051	31.011	0.002		
Wrist Posture x Compartment	0.341	154.000	0.002		
Condition Contraction x Compartment	0.116	308.000	0.000		
Wrist Posture x Condition Contraction x Compartment	0.191	616.000	0.000		

RING FLEXION					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Wrist Posture	0.030	2.000	0.010	0.610	0.553
Condition Contraction	0.226	1.977	0.114	8.774	0.002
Compartment	3.131	3.458	0.905	9.376	0.000
Wrist Posture x Condition Contraction	0.037	3.360	0.011	1.457	0.240
Wrist Posture x Compartment	0.198	14.000	0.014	3.918	0.000
Condition Contraction x Compartment	0.412	28.000	0.015	8.475	0.000
Wrist Posture x Condition Contraction x Compartment	0.032	56.000	0.001	0.822	0.819
Error					
Wrist Posture	0.479	22.000	0.022		
Condition Contraction	0.284	21.751	0.013		
Compartment	3.673	38.034	0.097		
Wrist Posture x Condition Contraction	0.277	36.955	0.007		
Wrist Posture x Compartment	0.555	154.000	0.004		
Condition Contraction x Compartment	0.535	308.000	0.002		
Wrist Posture x Condition Contraction x Compartment	0.429	616.000	0.001		

RING EXTENSION					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Wrist Posture	0.502	2.000	0.251	36.307	0.000
Condition Contraction	0.079	1.921	0.041	4.717	0.021
Compartment	7.294	2.614	2.791	38.872	0.000
Wrist Posture x Condition Contraction	0.014	3.572	0.004	1.313	0.283
Wrist Posture x Compartment	0.499	14.000	0.036	15.512	0.000
Condition Contraction x Compartment	0.189	28.000	0.007	6.651	0.000
Wrist Posture x Condition Contraction x Compartment	0.040	56.000	0.001	1.897	0.000
Error					
Wrist Posture	0.152	22.000	0.007		
Condition Contraction	0.185	21.135	0.009		
Compartment	2.064	28.749	0.072		
Wrist Posture x Condition Contraction	0.118	39.294	0.003		
Wrist Posture x Compartment	0.354	154.000	0.002		
Condition Contraction x Compartment	0.312	308.000	0.001		
Wrist Posture x Condition Contraction x Compartment	0.230	616.000	0.000		

Accuracy

NRMSE Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Wrist Posture	0.018	2.000	0.009	6.476	0.006
Task Finger	0.001	1.000	0.001	1.425	0.258
Direction of Force	0.044	1.000	0.044	13.206	0.004
Contraction Condition	0.066	1.389	0.048	40.795	0.000
Wrist Posture x Task Finger	0.000	2.000	0.000	0.484	0.623
Wrist Posture x Direction of Force	0.014	2.000	0.007	7.890	0.003
Task Finger x Direction of Force	0.000	1.000	0.000	0.065	0.804
Wrist Posture x Task Finger x Direction of Force	0.001	2.000	0.001	3.388	0.052
Wrist Posture x Contraction Condition	0.001	3.347	0.000	1.190	0.329
Task Finger x Contraction Condition	0.001	1.885	0.000	1.209	0.316
Wrist Posture x Task Finger x Contraction Condition	0.001	8.000	0.000	0.831	0.578
Direction of Force x Contraction Condition	0.003	4.000	0.001	2.536	0.053
Wrist Posture x Direction of Force x Contraction Condition	0.001	2.963	0.000	1.492	0.235
Task Finger x Direction of Force x Contraction Condition	0.000	2.448	0.000	0.620	0.577
Wrist Posture x Task Finger x Direction of Force x Contraction Condition	0.000	3.618	0.000	0.479	0.733
Error					
Wrist Posture	0.031	22.000	0.001		
Task Finger	0.010	11.000	0.001		
Direction of Force	0.036	11.000	0.003		
Contraction Condition	0.018	15.279	0.001		
Wrist Posture x Task Finger	0.007	22.000	0.000		
Wrist Posture x Direction of Force	0.020	22.000	0.001		
Task Finger x Direction of Force	0.004	11.000	0.000		
Wrist Posture x Task Finger x Direction of Force	0.004	22.000	0.000		
Wrist Posture x Contraction Condition	0.010	36.816	0.000		
Task Finger x Contraction Condition	0.006	20.734	0.000		
Wrist Posture x Task Finger x Contraction Condition	0.008	88.000	0.000		
Direction of Force x Contraction Condition	0.011	44.000	0.000		
Wrist Posture x Direction of Force x Contraction Condition	0.008	32.590	0.000		
Task Finger x Direction of Force x Contraction Condition	0.003	26.931	0.000		
Wrist Posture x Task Finger x Direction of Force x Contraction Condition	0.007	39.795	0.000		

Correlation					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Wrist Posture	0.000	2.000	0.000	0.285	0.755
Task Finger	0.005	1.000	0.005	7.602	0.019
Direction of Force	0.007	1.000	0.007	20.833	0.001
Contraction Condition	0.017	1.541	0.011	6.997	0.009
Wrist Posture x Task Finger	0.001	2.000	0.000	1.312	0.290
Wrist Posture x Direction of Force	0.001	2.000	0.000	1.776	0.193
Task Finger x Direction of Force	0.000	1.000	0.000	0.038	0.848
Wrist Posture x Task Finger x Direction of Force	0.002	2.000	0.001	2.425	0.112
Wrist Posture x Contraction Condition	0.004	2.221	0.002	1.558	0.230
Task Finger x Contraction Condition	0.001	1.403	0.001	0.286	0.678
Wrist Posture x Task Finger x Contraction Condition	0.003	2.006	0.002	1.200	0.320
Direction of Force x Contraction Condition	0.006	1.781	0.003	3.024	0.077
Wrist Posture x Direction of Force x Contraction Condition	0.002	2.191	0.001	1.266	0.303
Task Finger x Direction of Force x Contraction Condition	0.002	3.000	0.001	2.562	0.072
Wrist Posture x Task Finger x Direction of Force x Contraction Condition	0.003	2.761	0.001	1.628	0.206
Error					
Wrist Posture	0.015	22.000	0.001		
Task Finger	0.007	11.000	0.001		
Direction of Force	0.004	11.000	0.000		
Contraction Condition	0.027	16.952	0.002		
Wrist Posture x Task Finger	0.006	22.000	0.000		
Wrist Posture x Direction of Force	0.004	22.000	0.000		
Task Finger x Direction of Force	0.015	11.000	0.001		
Wrist Posture x Task Finger x Direction of Force	0.008	22.000	0.000		
Wrist Posture x Contraction Condition	0.025	24.426	0.001		
Task Finger x Contraction Condition	0.030	15.432	0.002		
Wrist Posture x Task Finger x Contraction Condition	0.030	22.064	0.001		
Direction of Force x Contraction Condition	0.020	19.595	0.001		
Wrist Posture x Direction of Force x Contraction Condition	0.015	24.104	0.001		
Task Finger x Direction of Force x Contraction Condition	0.010	33.000	0.000		
Wrist Posture x Task Finger x Direction of Force x Contraction Condition	0.020	30.369	0.001		

APPENDIX B. Ethics Approval and Consent Form

McMaster University — Inspiring Innovation and Discovery

McMaster University Research Ethics Board (MREB)

c/o Research Office for Administrative Development and Support, MREB Secretariat, GH-305, e-mail: ethicsoffice@mcmaster.ca

CERTIFICATE OF ETHICS CLEARANCE TO INVOLVE HUMAN PARTICIPANTS IN RESEARCH

Application Status: New ☑ **Addendum** ☐ **Project Number:** 2014 071

TITLE OF RESEARCH PROJECT:

Effect of wrist posture and rate of force development on finger control

Faculty Investigator(s)/ Supervisor(s)	Dept./Address	Phone	E-Mail
P. Keir	Kinesiology	23543	pjkeir@mcmaster.ca
Student Investigator(s)	**Dept./Address**	**Phone**	**E-Mail**
S. May	Kinesiology		mayse2@mcmaster.ca

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

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

☑ The application protocol is cleared as revised without questions or requests for modification.

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

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

Reporting Frequency: **Annual:** Apr-24-2015 **Other:**

Date: Apr-24-2014 **Acting Chair, Dr. D. Pawluch**

March 1, 2014

Letter of Information and Consent

Effect of wrist posture and rate of force production on finger control and independence

Investigators: Steve May and Dr. Peter Keir

Principal Investigator: Dr. Peter Keir
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Purpose of the Study
When humans are asked to move a single finger or apply force voluntarily with a single finger, movement and/or force tends to be produced by the other fingers as well, this is called "enslaving". The dependence between fingers is due to both mechanical connections between muscles and our ability to control the muscles. Forces may be transmitted from one tendon to another through connections between your tendons, which may be changed by flexing or extending the wrist. Additionally, the speed at which force is produced may affect our ability to control the action, and also change the independence of the fingers. The purpose of this study is to evaluate the effects of wrist posture and "speed of contraction" on enslaving, throughout submaximal efforts.

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, will be recorded. Immediately following this you will have recording electrodes placed over 8 muscles of the forearm. These electrodes allow us to record the activity in the muscles that control your fingers. To know how active your muscles are, we first need to determine the maximum activity for each muscle through a series of tests for each muscle. The apparatus will be placed on an adjustable table to measure individual finger forces. There will be padding on the table for your elbow and wrist. For the protocol, you will be seated with your forearm secured on top of the table so that your elbow is bent at 120 degrees, your thumb will be pointing up and your wrist in neutral (straight) posture. You will be required to exert finger forces both forward (flexion) and backward (extension) with your fingers in 4 adjustable padded rings, which will not move while you contract. You will perform a series of maximal contractions for flexion and extension, of all fingers. After maximal force for each finger is determined, a series of trials at 25% your maximum will be performed, with 30 seconds between consecutive trials. A second series of finger flexion and extension contractions will then be performed. "Ramp" exertions will involve an increase of force up to 50% your maximum (over 2 or 5 seconds), a brief hold, and then ramp back down to zero (in 2 or 5 seconds). These exertions will be performed at two different "speeds", and at three different wrist postures (30°

flexion, 0° neutral, and 30° extension). The index finger and ring finger will be the only two fingers to perform the submaximal contractions, and 60 seconds of rest will be given between trials. A total of 44 trials will be performed, and your participation will require about 2 hours in the lab.

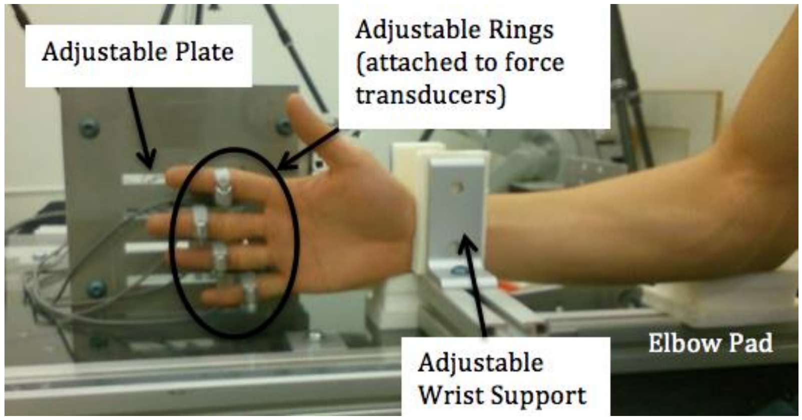

Figure 1. The apparatus being used, not shown here are the forearm electrodes

Potential Harms, Risks or Discomforts:
There is minimal risk associated with participation in this study. You may experience some muscle soreness as a result of the maximal exertions, however this is rare, and will be reduced furthermore with plenty of rest opportunities. We will be using a hypoallergenic adhesive to attach the electrodes to your skin. Although very rare, you may experience a temporary reaction to the adhesive from the surface electrodes. Should you experience any serious discomfort following the study, please contact the principal investigator, Dr. Peter Keir. Due to the nature of the protocol, you will not be allowed to participate if you have been diagnosed with high blood pressure, have an allergy to adhesives, or have a hand, wrist, arm, or shoulder injury/pain. If you have experienced an injury to any of these body parts that causes current pain, or has a chronic effect on your limb function you will be excluded from this study.

Potential Benefits
We hope to evaluate the mechanical and neural restrictions related to the lack of independent finger movement, by manipulating wrist posture, and rate of force development. The research will not benefit you directly.

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

Confidentiality:
Your identity will be kept confidential 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 of you taken for use in publications and presentations. Photo data will only be used with your consent. The information directly pertaining to you will be locked in a cabinet for a maximum of 15 years. Only Dr. Keir will have access to this information during that time, after which it will be destroyed

Participation:
Your participation in this study is voluntary. If you decide to participate, you can decide to stop at any time, even after signing the consent form or part-way through the study. If you drop out of the study, your data will be destroyed unless you indicate otherwise. If you decide to stop participating, 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. Keir or Steve May. 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 2014.

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 Steve May at mayse2@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 Steve May 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 this email address ____
Or to this mailing address: ____
____

… _____No, I do not want to receive a summary of the study's results.

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

Photo

Yes _____
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