Task-Related Variations in the Surface EMG
of Human First Dorsal Interosseous

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Abstract

Results from animal and human studies question the traditional view of a homogeneous organization of the motorneuron pool. Single muscles may be organized topographically into task groups that correspond with an intraspinal somatotopic organization. The aims of this study were to determine if: i.) there was differential activation in different locations of the first dorsal interosseous (FDI) muscle during a given task, ii.) the differential activation related to directional requirements and/or end goal of the task, and iii.) there was an anatomical pattern to the differential activation.

Twenty-six healthy right-handed participants carried out 48 isometric finger/hand contractions [8 tasks x (3 M waves + 3 active contractions)] in sitting while surface EMG was collected from 4 bipolar sites on the FDI muscle simultaneously. Index finger abduction and flexion forces were collected using 2 orthogonally placed load cells. The tasks were: abduction pre, flexion, diagonal, 30% abduction + 30% flexion, 30% flexion + 30% abduction, pinch, power, and abduction post. Mean peak integrated EMG (IEMG; smoothed over 100ms and integrated over contraction period) for each task was normalized to site and task specific mean M waves. We found differential IEMG across sites for all tasks, which further differed based on task direction and end goal. The anatomical pattern of the differential IEMG was such that there was always greatest activation in the distal ulnar site. We conclude that there are task-related variations in activation across locations of the human FDI muscle. The organization of the nervous system at the level of the muscle is not necessarily an “all-or-none” phenomenon.
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Introduction

Over half a century ago, Denny-Brown stated “too little is known of the normal behavior of muscles and of the process called ‘willed movement’ to permit the deductions that some investigators have claimed on the basis of differences seen in the electromyogram in disease” (Denny-Brown, 1949). Although much progress has been made since the days of Denny-Brown, several issues remain for a more complete understanding of coordinated movement (Cope, Sokoloff, & Clark, 1996). Contrary to what our current science textbooks teach, it has become increasingly evident that muscles are not simply homogenous units, activating in an all-or-none fashion during a motor task (Kernell, 1998). There is much heterogeneity present in a muscle, and it’s activation during coordinated movement merits further investigation.

A number of studies using both animal and human models have given credence to the idea of non-uniformity of motorneuron pool activation during a given task. These findings question the traditional view of a homogeneous organization of the motorneuron pool by proposing that the muscle may be organized topographically into task groups that correspond with an intraspinal somatotopic organization. Topographic organization, also known as somatotopic organization, refers to the idea that central organization (spinal cord) coincides with its peripheral inputs (muscle) in the form of a peripheral topography. For example, the spinal cord may be organized rostrocaudally in a way that mimics its
inputs to a given muscle unit: rostral inputs may influence medial muscle locations, whereas caudal inputs may influence lateral parts (or vice versa). Alternatively, the somatotopic organization may coincide with proximal/distal muscle locations.

This organization may be related to task grouping at the muscle level. For the purpose of this proposal, task groups refer to groupings of motor units within a muscle that are recruited differentially for a given task. At this point, it is unclear how the nervous system at the level of the spinal cord defines a task. We are uncertain what input to these motorneurons, and more specifically which task factors, may be most influential in driving this organization if it does indeed exist.

The focus of this proposal was to determine whether individual muscles and their respective motorneuron pool meet the constraints of tasks with different requirements through task group specialization of motorneurons (i.e. motor programs) using alternative synergistic activity of motor units within a single muscle (potentially via somatotopic organization). These issues are related to the organization of motor control at the spinal cord level and can be clarified by fine resolution electromyography (EMG). EMG has the capability to characterize the details of motorneuron activity and recruitment in a way that may elucidate the nervous system’s organization and control of specific tasks.

Our broad research goal was to gain insight into how the neuromuscular system is organized for movement, as studied at the level of a single human muscle and its motorneuron pool. More precisely, our goal was to determine if a single human muscle,
the first dorsal interosseous (FDI), is differentially activated (as measured by a surface EMG array) in a task-specific manner thus allowing us to make inferences about the potential functional somatotopic organization of the spinal cord. We aimed to elucidate the influence of two specific task factors on this organizational control by systematically manipulating the effect of: i.) movement direction in extrinsic space, and ii.) end goal of two functional tasks. Our overall research questions are delineated below.

Questions:

1. Is there inhomogeneous activation in different locations of a single muscle (first dorsal interosseous; FDI) simultaneously during a given task.

2. Is the differential activation related to:
   a. Directional requirements of the task
   b. End goal of the functional task

3. Is there an anatomical pattern to the differential activation (i.e. proximal/distal or radial/ulnar)

There is evidence of differential activation across a single muscle driven by task requirements in both animal and human models (see Background). However, to our knowledge, an investigation of the direct effect of systematically manipulating these specific task factors/requirements and objectively comparing muscle activation in a single muscle in humans via a surface EMG array had never been carried out. Additionally, the majority of the previous studies investigating an aspect of this inhomogeneous activation
in humans utilized an anatomically partitioned muscle, extremely small sample sizes, and/or irreproducible methodology. Furthermore, some studies had *inadvertently* found this non-homogeneous activation while investigating an entirely different experimental question.

Addressing this gap in knowledge has significant implications with regards to our overall understanding of motor control at the spinal cord level. If indeed there is inhomogeneous activation across different locations within a single muscle that is based on task requirements, it will allow us to: i.) gain a more complete understanding of the peripheral pattern of this organizational control in a healthy human model potentially shedding light on mechanisms underlying muscle fiber differentiation and motorneuron properties (Kernell, 1998), ii.) make inferences regarding the anatomical organization of the human spinal cord related to these peripheral patterns, iii.) gain insight into the influence of the specific task factors, and iv.) potentially elucidate some of the movement patterns we see in populations with pathology in applied studies of the neuromuscular system. The differential activation observed peripherally may mirror the somatotopic organization at the cord level, which casts doubt on the traditional view of homogeneous organization of the motorneuron pool.
Background and Significance

Motorneuron Pool Organization

There are many “problems” that the nervous system must attempt to solve, including: how to produce a stable gradable force, how to use force production and its grading mechanisms for tasks of different peripheral requirements, how to adapt these mechanisms to long-term use, and how to integrate the individual muscle and its motorneurons into different motor programs (Kernell, 1992). These “problems” of motor control are solved in part by the neuromuscular unit.

Within a typical given muscle there are thousands of fibers organized into smaller working units, termed the motor unit (Sherrington, 1925). Sherrington originally defined the motor unit as a single motor neuron and all the muscle fibers innervated by it. The definition was expanded to the motor neuron, its dendritic tree, the axon, and all the muscle fibers it innervates (Denny-Brown, 1949). The motorneuron pool is typically defined as the group of motor neurons that innervate all of the muscle units of a given muscle. Motor neurons innervating one muscle are clustered into an elongated motor nucleus within the ventral spinal cord, extending over two to four segments (Kandel, Schwartz, & Jessell, 2000).
Electrical activity in a muscle, reflective of the aggregate activity of the motorneuron pool of that muscle, is typically recorded as EMG using fine wire, needle, or surface electrodes. During muscle contraction, motor neurons are typically recruited in an orderly fashion, from-smallest to-largest; this recruitment pattern is known as the size principle of motor neuron recruitment (Henneman, 1957). Each motor neuron has thousands of synaptic inputs, the majority of which are from interneurons. The sum of excitatory and inhibitory effects of these inputs determines if the neuron reaches threshold, fires, and takes part in a motor program. For the purposes of this proposal, a motor program will be referred to as an abstract representation of a certain “task” that results in the production of a coordinated movement (Schmidt & Lee, 2005). A task may be composed of one muscle and its representative muscle units carrying out one movement (i.e. FDI muscle for finger abduction), or many muscles working together to complete a movement (i.e. multiple hand muscles for grasp).

Motorneuron pool organization has traditionally been looked at as a muscle-specific columnar nucleus intraspinally composed of all of the motor neurons that innervate muscle units of one muscle. These motorneuron pools have been viewed as functional units that are uniformly activated for all motor programs, and movement has been associated with the action of the whole muscle-tendon complex. Contrary evidence supports differential recruitment of motor unit populations in regions of whole muscle in humans and animals during different movements (Hensbergen & Kernell, 1992; Hoffer et
al., 1987; Riek & Bawa, 1992; ter Haar Romeny et al., 1982). Additionally, there is suggestion from the literature that there may be somatotopic organization intraspinally (Hensbergen & Kernell, 1992; Hoffer et al., 1987; Romanes, 1951; Swett, Eldred, & Buchwald, 1970).

Looking at the organization of the motorneuron pool from a task group perspective could change the focus of our understanding from a purely anatomical perspective to more of a functional one. This perspective may provide insight into how the central nervous system solves problems specific to the requirements of a task or movement, beyond the neuroanatomy of the participating structures.

**Theoretical Overview**

At the root of the discussion of inhomogeneity of muscle activation/motorneuron recruitment lays the proposed mechanism. In our view, three somewhat distinct theoretical models have been proposed: i.) anatomical partitioning, ii.) task group theory, and iii.) ensemble theory (Cope et al., 1996; Kernell, 1992; Riek & Bawa, 1992).

Anatomical partitioning theory uses a comparison of muscle regions based on architectural and innervational characteristics. This comparison is used to determine if the primary nerve branching pattern throughout muscle may or may not have direct relevance for the central programming of motorneuron behavior (Segal, Catlin, Krauss,
Merick, & Robilotto, 2002). It refers to distinct anatomical subvolumes that may exist related to functional organization. This theory has some support in certain muscles that have natural anatomical partitioning (i.e. extensor carpi ulnaris, flexor carpi ulnaris, flexor digitorum profundus) (Segal et al., 2002), shown to be differentially active during a given task.

Task group theory, on the other hand, is based on the idea of the integration of muscle and motorneurons into motor programs, referred to as task-related use of motorneuron pools (Kernell, 1992). This theory proposes that there is a fractionation of the interneuronal pool whereby differential inputs selectively influence different portions of the motorneuron pool based on task. Spinal interneurons may distribute their input to specific parts of the motorneuron pool, with gradients of intensity of inputs allowing task flexibility in motorneuron recruitment patterns (Kernell, 1992).

Ensemble theory is yet another theoretical perspective that proposes that the organization of motor unit selection is based on task, extending beyond boundaries of traditionally defined single muscles (Cope et al., 1996; Riek & Bawa, 1992). In effect the ensemble theory builds off of the task group theory and extends it to groups of muscles, or multi-muscular synergies. The size principle of motorneuron recruitment has been shown to be in true in most studies on single muscle contraction, but it does not apply to all multi-muscular motor tasks (Segal et al., 2002). Its boundaries may not be restricted to a single muscle, and there may be other principles that are involved to help
control different movement parameters (Cope et al., 1996; Kernell, 1992; ter Haar Romeny et al., 1982). Riek and Bawa demonstrated that the size principle held true for the extensor carpi radialis (ECR), whereas the extensor digitorum communis (EDC) had size-ordered recruitment within task groups (Riek & Bawa, 1992).

Most of the available evidence regarding muscle activation and neuromuscular organization at the spinal cord level supports components of each of the aforementioned theoretical approaches. For the purpose of this proposal, we focused on the task group theory in its broader definition, encompassing the more salient features of both the ensemble and anatomical partitioning theories. We investigated a single muscle with two head, the first dorsal interosseous (FDI), utilizing its anatomy to guide our exploration. Additionally two of our task conditions attempted to probe the relevance in multimuscular synergies (i.e. ensemble theory) indirectly through use of two multimuscular functional tasks: key pinch and power grasp. Relevant literature is cited below, most of which supports an explanation of mechanism built upon the foundation of task theory, with components of the other two theories intertwined.

**Anatomical Partitioning**

The anatomical partitioning theory refers to compartmentalization within a muscle, which doesn’t necessarily concur with the premise of task grouping and
corresponding somatotopic organization. Certain muscles possess a natural anatomical subdivision or compartmentalization whereby there are non-overlapping subvolumes within the muscle. This compartmentalization may or may not be specifically related to functional organization. This is also commonly referred to as neuromuscular partitioning, which Kernell’s group defined but didn’t feel answered the question of motorneuron pool organization (Kernell, 1998). Stuart’s group succinctly summarized the idea as that of a neuromuscular compartment whereby separate muscle “subvolumes” are innervated exclusively by the primary branch of a muscle nerve (Stuart, Hamm, & Vanden Noven, 1988).

One of the earliest studies in this area found the gastrocnemius muscle in cats to have distinct subvolumes, each with a uniform distribution of fiber types; proximal lateral contained fast glycolytic fibers whereas the distal compartment had some fast glycolytic fibers as well as some slow oxidative fibers (English & Letbetter, 1982). The authors proposed that their findings support the idea of segregation of muscle fibers in the lateral gastrocnemius into compartments based on motor unit affinity. Upon renewed data analysis of these findings, it was discovered that fiber type variation is also present within the singular compartments (Kernell, 1998). In a review, Kernell brings up the provocative point that compartmentalization and fiber type regionalization can vary independently, and may reflect a more general organizational principle that is not limited to the compartmentalization itself (Kernell, 1998). In this way, the organizational
principles (i.e. fiber type regionalization) are most likely not limited by the anatomical confines of each compartment, but rather are true of each individual compartment as well.

Stuart’s group reviewed many studies that have indeed confirmed the existence of neuromuscular compartmentalization in many muscles, with some exceptions and variability muscle to muscle. One key point they made was that “architectural features alone will never reveal the versatility of arrangements and mechanisms for operation of the segmental motor-control system” (p.444) (Stuart et al., 1988). They brought up, and we agree with the idea that the task group theory subsumes the true elements of the anatomical partitioning theory in certain muscles during certain tasks. In the least, the anatomical partitioning work helps us keep in mind the importance of considering architectural features of the system (i.e. pennation angle, two-headed muscles) as well as biomechanical constraints (i.e. moment arm) when investigating the control of coordinated movements.

**Muscle Regionalization**

Muscle regionalization is often mistaken for anatomical partitioning. Although it is also based on anatomy, it is a different phenomenon. Muscle regionalization refers specifically to regional intramuscular differences in fiber type composition (Kernell,
Jabre and his colleagues describe how this can be present in 4 different ways: i.) primary branches of the nerve innervate separate muscle portions (‘neuromuscular partitioning’), ii.) intraspinal motorneuron alignment that corresponds with peripheral intramuscular sites, iii.) differential activation during different motor tasks, and iv.) muscle fibers with different functional properties are unevenly distributed throughout the muscle (Jabre, Hallet, Lemon, & Kernell, 2000). For the purpose of this proposal, muscle regionalization will refer to differential distribution of muscle fiber types within a given muscle, which is not synonymous with the compartmentalization of muscles (i.e. two heads of the biceps) referred to by the anatomical partitioning theory. Muscle regionalization exists in single compartment muscles as well.

Muscles that have marked fiber type regionalization have been shown to have a corresponding regionalization of activity peripherally, but this varies based on context of the task (Kernell, 1998). Wang & Kernell found that degree of regionalization in rat hindlimb muscles related to the location of the muscle relative to the limb center: muscles towards the outside of the limb had more type I fiber regionalization, with these slow fibers typically being located closer to the limb center (Wang & Kernell, 1998). These authors built upon this work, later finding that the distribution of type I muscle fiber types in five rat hindlimb muscles decreased as you move distal in the limb. Additionally, these fibers were concentrated in the outer regions of the limb distally, as compared to proximally (Wang & Kernell, 2000). In subsequent studies, they denervated
and then re-innervated muscles, and found that both fast and slow motor axons ended up in their typical intramuscular regions after re-innervation, partially dependent upon location of the muscle within the limb (Wang & Kernell, 2002). The authors suggested that these proximal-distal differences may relate to early developmental stages of muscle differentiation.

Although depth within the muscle is a strong factor related to fiber type regionalization, it has not been found to be true of all muscles, particularly in humans (J. Polgar, M.A. Johnson, D. Weightman, & D. Appleton, 1973). Fiber distribution has also been shown in medio-lateral as well as proximal-distal distributions (Kernell, 1998). This neuroanatomical organization must be driven by and/or related to function. Since differential motor unit recruitment is not only present in muscles with regionalized muscle fiber types (i.e. cat gastrocnemius), then regionalization of muscle fibers does not solely explain differential muscle activation (Kernell, 1998). Additionally, differential activation in one muscle has been seen to change based on motor task, which doesn’t fully support this explanation, but rather that of task grouping. We will go on to explore the potential physiological and anatomical mechanisms proposed to be behind task grouping.
Functional Intraspinal Somatotopic Organization

One potential mechanism for this inhomogeneous muscle activation/motorneuron recruitment pattern is a functional somatotopic organization at the spinal cord level, as has been demonstrated in the motor cortex. Attempts to elucidate the specialized control of muscles have led some to the conclusion that spinal cord organization has many similarities to that of the brain in terms of somatotopic organization, processing, and plasticity (Flanders, 2005; Windhorst, 1996). A predominant feature of the cerebral cortex is that of a flexible functional somatotopy: each behavior or function is spread over the surface of certain cortical areas on an underlying peripheral topography (Flanders, 2005). Scientists are now inquiring whether the spinal cord too has a similar topographical organization and how this may relate to motor control.

Flanders and colleagues conducted a study using two bipolar surface EMG set-ups on the FDI muscle (in addition to 5 other hand muscles) investigating hand synergies during certain tasks requiring different shaping and tracing. They found that hand muscle activation was highly distributed across muscles, somewhat analogous to that of the hand representation somatotopy in the cortex (Weiss & Flanders, 2004). The authors went on to propose that the many ways that the hand shapes may be likened to postural synergies, and that motor units take part in multiple synergies. The organization of hand movement
at the spinal cord level might be widely distributed in a fractured somatotopy just like the
cortex, which would facilitate recruitment of appropriate groups of muscles, or in the
case of a single muscle, appropriate motor units for the task at hand (Weiss & Flanders,
2004). These task or motorneuron groups can be considered synergies. In an extensive
review of this topic, Kernell reiterated that a common denominator in organization of the
nervous system is topographical organization: similarly active motorneurons typically lie
in regions of close proximity (Kernell, 1992).

Animal models have supported a type of underlying anatomical
distribution/topography that plays a role in this control. The ventral divisions of the
primary rami of the cat lumbar spinal region appear to supply muscles acting on the hip,
whereas dorsal divisions supply hip and knee joints; cranial ventral parts control knee
extensors, and caudal dorsal parts control ankle dorsiflexors and toe extensors (Romanes,
1951). Hensbergen and Kernell found selective activation in the posterior regions of the
cat peroneus longus muscle during hindlimb standing or take-off for a jump, whereas
anterior regions were predominantly active during preparation for landing (Hensbergen &
Kernell, 1992). Two intriguing aspects of their findings are: i.) although all of the units
of this muscle should exert their force in the same direction, different portions of the
muscle were active for different tasks, and ii.) both regions of the muscle were equally
active during swing, demonstrating that this phenomenon was only present during
selective parts of the task. This evidence of topographical localization of a task within a
single muscle supports the possibility that control of muscle/motorneuron activity is based, at least in part, on anatomical distribution or somatotopy related to task.

Whether it is somatotopically organized or not, it certainly appears as if topography is indeed one guiding factor. Hoffer et al. looked at the cat sartorius muscle in an effort to examine how a single motorneuron pool controls three different functions using two anatomically distinct portions (anterior and medial) of one muscle during locomotion (Hoffer et al., 1987). Microelectrodes were surgically implanted in the L5 ventral roots of cats and the firing of single motorneurons (dots in Figure 1) projecting to the sartorius muscle were recorded during walking on a treadmill. The firing of the single motor neuron was then correlated to the surface EMG ($r^2$ values). Figure 1 illustrates their findings. Stance and swing phases were subdivided into an $E_{2,3}$ phase of stance and an $F$ and $E_1$ phase of swing. Unit Q8A1 (Figure 1A) was active during the $E_1$ phase of swing and was more correlated with the surface EMG from the anterior compartment of sartorius (top trace, 1A) than the medial compartment (bottom trace, 1A). Unit MSU10 (Figure 1B) was active during the $F$ phase of swing and was more highly correlated with the surface EMG from the medial compartment of sartorius (bottom trace, 1B) than the anterior compartment (upper trace 1B).
Correlation profiles of 2 different sartorius motorneurons’ firing frequency (Q847, MSU10) during E1 phase (A) and F phase (B) of gait with sEMG profiles of different portions of the muscle; SA-a: anterior sartorius SA-m: medial sartorius. Unit Q8A7 was active during the E1 phase of swing and was more correlated with the surface EMG from the anterior compartment of sartorius (top trace, 1A) than the medial compartment (bottom trace, 1A). Unit MSU10 was active during the F phase of swing and was more highly correlated with the surface EMG from the medial compartment of sartorius (bottom trace, 1B.) than the anterior compartment (upper trace 1B). (Hoffer et al., 1987).

Figure 1: Functional segregation of cat sartorius motorneurons during swing phase of gait
Based on the pooled results from several motor neurons, the authors interpreted their results as indicating that the motorneuron pool of the cat sartorius muscle has three functional task groups: one for knee extension (stance), one for knee and hip flexion (early swing), and one for knee extension and hip flexion (late swing), each of which is partitioned into separate units located topographically within the muscle. They proposed a schematic of the potential organization depicting anatomical and functional segregation of these three independently recruitable motorneuron task groups (Figure 2). The schematic shows a transverse section of the sartorius muscle (left) as shown by the dashed line in the diagram on the right. The anterior portion of the sartorius muscle (bottom left labeled “anterior”) is only innervated by E₁ and E₂-3 motorneurons whereas the medial sartorius is innervated solely by F-task motorneurons. Consistent with traditional perspectives, the individual cell bodies (F, E₁, E₂-3) are assumed to represent a single motor nucleus in the ventral horn.
Kernell (1992) suggested three general organizational principles common to the entire central nervous system: i.) nerve endings carrying the same function go to the same place, ii.) neurons executing given functions lie together, and iii.) motoneurons of different functional groups (i.e. flexion vs. extension) show different localization within the spinal cord (Kernell, 1992). When the ventral roots of the cat peroneus longus
muscle were selectively and repetitively stimulated to deplete the glycogen within their muscle fibers, cranial motorneurons were found to preferentially innervate anterior muscle portions (Figure 3, bottom left) whereas caudal motorneurons innervated primarily posterior portions (Figure 3, bottom right).

A topographical relationship also exists in cat hindlimb muscles between the site of the muscle fibers within that single muscle and the intraspinal site of their respective motorneurons (Swett et al., 1970).

During tasks of isometric elbow flexion, forearm supination, shoulder external

Figure 3: Topographic relationships between intraspinal and intramuscular sites of motorneurons
Cranial cat motorneurons preferentially innervated anterior muscle locations, whereas caudal motorneurons preferentially innervated posterior locations; insets are normalized data showing relative numbers of depleted muscle fibers in different muscle regions (anterior, middle, posterior; means +/- SE; n=9 (Kernell, 1992).
rotation, or a combination movement in humans, exclusive supination muscles units were active medially vs. flexion units laterally in the long head of the biceps muscle, *despite common wrist torques* (ter Haar Romeny et al., 1982). This sort of regionalization did not solely follow an innervational or anatomical partitioned pattern; therefore some other organization principles must be involved. In this regard, the anatomical partitioning theory doesn’t fully explain the mechanism, whereas the task group theory with corresponding somatotopic spinal organization may.

**Synaptic Regionalization Within Motorneuron Pools**

Spinal interneurons may be the key driving force to this organization through distribution of their input to specific parts of the motorneuron pool, which may direct spatial coordination of muscle pattern activation (Kernell, 1992). The interneuronal pool may display a pattern of inhomogeneity (Figure 4); each interneuron (IN-1, IN-2) may give input to all parts of the pool (MN-pool A, MN pool B, or MN pool C), but there may be gradients of intensity of input related to synaptic effects whereby motorneuron recruitment patterns could be appropriately flexible related to task. A certain task may require muscle coordination such that different distributions of activity are present within individual motorneuron pools (Kernell, 1992).
There is indirect evidence that inputs to the motorneuron pool may be distributed based on task, with different inputs having different weightings on motor units (ter Haar Romeny et al., 1982). Kernell brought up a provocative point in his review: the intramuscular regionalization of fiber types might be a secondary effect of this centrally motivated inhomogeneous motorneuronal recruitment (Kernell, 1992).

Kandou and Kernell performed a study on the peroneus longus of anesthetized cats, which was considered a mechanically homogeneous muscle in its joint torque directional capabilities. Two conditions were studied: i.) stimulation of the superficial peripheral nerve innervating that muscle, and ii.) stimulation of the contralateral motor cortex. Peroneus longus muscular activity as measured by fine wire EMG appeared to be
stronger or more biased overall for the posterior portion as compared to the anterior portion, particularly when the stimulus was cortically driven (Kandou & Kernell, 1989).

In view of the fact that the anterior portions are innervated by rostral and posterior by caudal motorneurons, these data support the premise that various inputs to this motoneuron pool may differ with respect to the intraspinal distribution of synaptic effects on the motorneurons; different sets of synapses may be related to different tasks, and differ in their spatial distribution as well.

**Synergistic Activity of Motor Units Within a Muscle**

Consistent with the aforementioned somatotopic organization and flexible interneuronal biasing based on task, an extended explanation entails synergistic activity of motor units within one muscle. This synergism would be characterized by motorneuron activities that are synchronized, or groups of motorneurons that act together both temporally and spatially to perform a given task. For the purpose of this proposal, we will be concerned primarily with synergistic activation of motor units of a single muscle as opposed to synergies of many muscles, which is described more in depth by the ensemble theory. Evidence from some of the studies cited earlier that have found differential activation during combination movements, whether defined directionally in extrinsic space or by joint movement (i.e. flexion vs. supination), are supportive of this
In a group of healthy adults carrying out simple isometric finger tasks during a fatigue protocol, Zijdewind and colleagues found inhomogeneous FDI muscle activation across different muscle sites (Figure 5) (Zijdewind et al., 1995).

Figure 5: Schematic of right hand with superimposed coordinate system for FDI electrode sites
Coordinate system used in an attempt to objectify the localization patterns seen in the surface EMG of FDI based on 2 separate bipolar recording sites (Zijdewind, Kernell, & Kukulka, 1995).

Figure 6 demonstrates how FDI EMG at two different sites (EMG-1, EMG-2; 2\textsuperscript{nd} & 3\textsuperscript{rd} rows of 6A, 6B, 6C, 6D) in four different participants (6A, 6B, 6C, 6D) varied despite constant finger abduction force (1\textsuperscript{st} trace of 6A, 6B, 6C, 6D). For example, one participant (6B) had a simultaneous marked increase in EMG in one location (EMG-2)
with no change in another location (EMG-1) during a 60 second, 50% maximum isometric contraction.

What was even more interesting about their findings it that upon further data analysis, the investigators realized that the amount of inadvertent flexion or extension during isometric abduction of the index finger influenced the differential EMG in FDI. While

**Figure 6: Inhomogeneous EMG in FDI during a fatiguing isometric finger abduction task**

Simultaneous index finger abduction and rsEMG at different sites (EMG-1, EMG-2) of the FDI in 4 participants (A, B, C, D); rsEMG varied across sites (6B, 6C, 6D) despite constant finger abduction force (1st trace of 6A, 6B, 6C, 6D) (Zijdewind et al., 1995).

What was even more interesting about their findings it that upon further data analysis, the investigators realized that the amount of inadvertent flexion or extension during isometric abduction of the index finger influenced the differential EMG in FDI. While
isometrically holding an abduction force (Figure 7A, 2\textsuperscript{nd} trace), a simultaneous decrease in finger flexion (7A, 1\textsuperscript{st} trace) corresponded with a decrease in EMG at both sites (EMG-1, EMG-2), although greater at one site in particular (EMG-2), with only minimal changes in the abductor force. Zijdewind and colleagues referred to this as ‘task switching’ or changes in EMG distribution and muscle synergy during certain tasks (Figure 7) (Zijdewind et al., 1995).
The results support the premise that the FDI muscle is not necessarily handled homogenously but rather that the nervous system has several alternative ways to achieve the task successfully: by use of differential synergy of motor units in one muscle and/or possibly via multimuscular synergies (Zijdewind et al., 1995).

Along these same lines, the ter Haar Romeny study cited earlier (ter Haar Romeny et al., 1982) would be one in which the results could be interpreted as supportive of
synergistic activity of motor units within a muscle. Figure 8a demonstrates the recruitment of a single motor unit (upper trace) in the biceps brachii muscle when an isometric ramp flexion force (8a, lower trace) is produced while supination and external rotation are held constant; the unit is recruited at a given amount of flexion force. When an isometric supination force is maintained, and the flexion force added (8b, two middle traces), the unit is recruited at a higher flexion force. When an isometric pronation force is maintained and the flexion force added (8c, bottom two traces), the unit is recruited at a lower flexion force. These results were interpreted by the authors to demonstrate a differential motor unit recruitment driven by different linear combinations of task directions, which could be envisioned as a form of a single muscle synergy, or synergistic activity of motor units within a single muscle.
Intracellular recordings in cats have also shown that heteronymous Ia connections exist, supportive of organization of changing synergies. These connections are capable of meeting the larger repertoire of movements the forelimb must carry out (Fritz, Illert, de la Motte, Reeh, & Saggau, 1989). The constellation of evidence supporting somatotopic
 Task Group/Motor Program Specialization

Task group theory has some convincing support, particularly in relation to what is already known about the functional organization of the motor cortex. The idea of nervous system control based on task grouping, or motor programs, is not new and was originally based on findings in the cerebral cortex. A pivotal study in this area by Muir and Lemon supported task group specialization in corticomotorneuronal cells in the primary motor area of monkeys (Muir & Lemon, 1983). Figure 9 illustrates a monkey carrying out three different lever-squeezing tasks between the thumb and index finger (somewhat isometric ramp and hold): precision grip (pinch) of light and heavy force (9A) and power grip (9B) while pyramidal tract neuronal firing (histograms in second column, 9A & 9B) and fine wire EMG (post-spike facilitation; rectified) of the FDI (9A & 9B, third column) are measured simultaneously.

Corticomotorneuronal cells in the primary motor area were less active for the power grip (9B column 2, trace 3) compared to both the light (9A column 2, trace 1) and heavy force precision grips (9A column 2, trace 2), despite relatively comparable EMG (9A & B column 3). The authors concluded that the differential corticomotorneuronal
activity was discrete from that of the muscle activity, suggesting sub-populations of neurons were active during certain discrete hand tasks.

Figure 9: Task group specialization in corticomotoneuronal cells of monkeys during different hand tasks

Histograms (16 repetitions) of activity in the same cortical pyramidal tract neurons (PTN; column 2) and rectified fine wire FDI EMG (column 3) of the same muscle (FDI) during three different tasks (light precision grip (A upper trace), heavy precision grip (A lower trace), power grip (B)). Greater PTN activity during both precision grips (regardless of force) as compared to power grip despite similar EMG recordings in all 3 tasks (Muir & Lemon, 1983).

As noted earlier, Hoffer et al. found that motor units in the cat sartorius muscle were differentially active during the swing vs. stance phase during treadmill walking, indicating “task specificity” of motorneurons (Hoffer et al., 1987). Hensbergen & Kernell built upon this work, with evidence of preferential use of different muscle regions in peroneus longus muscle of the cat, not exclusively based on force direction. Using
chronically implanted EMG in the hindlimbs during voluntary movement, the authors found that different portions of the peroneus longus muscle were differentially active simultaneously during different behaviors (Hensbergen & Kernell, 1992). Figure 10 displays EMG from 2 different cats (1st & 2nd rows from one cat; 3rd & 4th rows from another) in the anterior portion (1st & 3rd row of traces) and the posterior portion (2nd & 4th row of traces) of the peroneus longus during swing phase of level ground walking (1st & 2nd column), standing on hindlimbs (3rd column) and preparing to land when lifted off the ground (4th column). As is evident from these traces, the posterior regions of this muscle were primarily active during standing on the hindlimbs, whereas the anterior portion was active when preparing to land. The authors proposed that interneuronal units that coordinate landing may be located such that they favor rostral motoneurons of the peroneus longus, whereas the ones that facilitate standing might be located more caudally.
Activation patterns in the flexor digitorum longus (FDL) and flexor hallucis longus (FHL) muscles (proposed anatomical synergists) of cats have been shown to be independent during treadmill walking (O'Donovan, Pinter, Dum, & Burke, 1982). FDL was primarily active during tasks including: just after foot liftoff, perturbed stance, jumps, fall, landings and paw-shake reflexes, whereas FHL was active throughout most

Figure 10: Inhomogeneous muscle activation in different portions of cat peroneus longus during voluntary behavior
Simultaneous EMG (raw in A,B,E,F,G,H; rectified/smoothed in C,D) in anterior (a-PERL) and posterior (p-PERL) peroneus longus portions of 2 cats (A,C,E,G & B,D,F,H). Primarily activation in posterior regions for standing (E&F) and anterior for preparation to land (G&H) (Hensbergen & Kernell, 1992).

Activation patterns in the flexor digitorum longus (FDL) and flexor hallucis longus (FHL) muscles (proposed anatomical synergists) of cats have been shown to be independent during treadmill walking (O'Donovan, Pinter, Dum, & Burke, 1982). FDL was primarily active during tasks including: just after foot liftoff, perturbed stance, jumps, fall, landings and paw-shake reflexes, whereas FHL was active throughout most
of stance. Since the motorneuron pool for these two muscles lie in the same column of the spinal cord, and the muscles themselves lie in parallel forming a common tendon, it may be that anatomy is not the only factor driving their motorneuron recruitment/activation. Their functional dissociation may be related to divergence of synaptic organization, driven by segmental interneurons, which may simplify the task at hand. Again, this may be supportive of either task grouping via motor programs, synaptic regionalization, or both.

English and colleagues studied the cat gastrocnemius muscle during free locomotion patterns, and EMG patterns emerged related to the four separate compartments. There was more activation in the distal compartments at slower speeds as opposed to more proximal activation at higher speeds, with more than one activation pattern being present (English, 1984). This may speak to task grouping, and potentially the importance of speed in driving this differential motorneuronal recruitment. What is clear from the literature is that some form of task grouping exists at the muscle level. What is not clear are which task factors or requirements drive this differential activation.

**Task Factors**

Although it isn’t clear how the nervous system defines a task, numerous task parameters appear to influence differential motorneuron pool activation and deserve
further discussion. It is possible that this is one way in which the nervous system defines task.

*Direction of Movement in Extrinsic Space*

Direction of movement within a task has been implicated as one relevant factor driving differential muscular activation. The term direction appears to be used relatively inconsistently across studies, not typically explicitly defined as being within extrinsic space or not. This proposal will view direction as that determined by movement in extrinsic space. A different study by ter Haar Romeny had results that could be viewed as supportive of the important influence of direction in differential motorneuron recruitment. Using bipolar wire EMG in the human biceps muscle, different patterns of motor unit recruitment were found: i.) units active during flexion were most lateral, ii.) units active during supination were most medial, iii.) units firing during combination movements were medial, and iv.) nonlinear units (didn’t depend on linear combination of flexion and supination forces) were central in location (ter Haar Romeny, van der Gon, & Gielen, 1984). The same muscle may carry out different movements but have “directional” innervation that leads to differential motorneuron recruitment (ter Haar Romeny et al. 1982).

Thomas et al.’s findings in the FDI, on the other hand, do not support the idea that
there is inhomogeneous activation (as measured by motor unit recruitment using spike-triggered averaging) driven by directional requirements. Their data using 2 fine wire bipolar recordings as well as surface EMG in the FDI muscle of 4 participants found similar recruitment order during index finger abduction vs. flexion vs. adduction with opposition to the thumb (Thomas, Ross, & Stein, 1986). One potential explanation for their results is that they did not isolate the two forces simultaneously. The authors did mention that there was a possibility that training may induce some inhomogeneous activation present in the results of other studies.

When investigators have referred to the differential recruitment within their studies as being directionally dependent, it is difficult to determine if it is direction of movement, static position, or the overall task itself driving the differential activation, because the actual definition of “direction” within the studies has been unclear. Biomechanical considerations, including direction of movement in extrinsic space, may necessitate diverse motor unit recruitment into synergies or groupings, and merits further investigation.

*Speed of Movement*

Yet another potential influential factor is that of movement speed. Tax et al. found greater biceps activation during isotonic flexion and extension movements as
compared to isometric contractions, whereas imposed movements and isometric movements were comparable (Tax, Denier van der Gon, Gielen, & Kleyne, 1990). The authors attributed their findings to differential activation of the alpha and gamma motorneuron pool during force tasks and slow movement tasks, despite comparable torque and/or movement requirements. As noted earlier, the study by English and colleagues in the cat gastrocnemius during free locomotion attributed their findings to speed as well. A relatively recent study of in vivo muscle activation of the guinea fowl lateral and medial gastrocnemius muscles showed increases in all muscle locations with increased speed of walking/running, whereas EMG changes were more variable related to the degree of incline (Higham & Biewener, 2008). We did not come across any other articles that specifically manipulated this variable with the intention of answering the question of whether speed is an influential factor in driving differential muscle activation.

**Joint Angle**

In addition to the parameters of movement direction and speed, joint angle also appears to contribute to this organizational control. Single bipolar surface EMG in the FDI varied during maximum pinching based on wrist angle in humans (Figure 11), having higher EMG levels with wrist in maximum flexion (11, top trace on right) vs. maximum extension (11, top trace on left) (Zijdewind et al., 1998). The EMG results
were not due to changes in recording conditions in that the M-wave before (11A), during (11B) or after (11C) maximum pinching did not change, further reinforcing that this differentiation in FDI drive is dependent in part on motor task, in this case operationalized by different wrist joint angles. It is currently unclear what other aspects of biomechanical leverage or anatomy may play a part in this organizational control.

**Figure 11: Altered motorneuronal drive to FDI in humans based on wrist joint angle**
Greater FDI EMG during maximum pinch with wrist in maximum flexion (column 2) vs. maximum extension (column 1). EMG differences not due to recording changes, evident by consistent M-waves before (A), during (B), and after (C) task (Zijdewind, de Groot, & Kernell, 1998).

During static tasks in humans, activation in forearm and upper arm musculature was different for an isometric as opposed to an isoinertial task, indicative of neural
commands being dependent on more than load or joint angle; there was differential activation for a position as opposed to a force matching task (Buchanan & Lloyd, 1995). Again, the relevance of these variables is not yet clear, although one can be certain that biomechanical task constraints likely play a large role and most likely correspond in some way to motorneuronal activation.

**Skill Requirements**

Beyond isolated single movement parameters associated with a given task, the question of the influence of overall skill requirements of a task arises as a factor. Based on findings of high variability in motor unit recruitment in two extensor carpi radialis muscles present only during imposed velocity tasks, Romaiguere et al. put forth the notion that motorneuron pool excitability is dependent on the experimental situations as well as task complexity (Romaiguere, Vedel, & Pagni, 1989). Results from a different study on the human flexor digitorum superficialis muscle investigating motor unit synchrony found that the degree of synchrony for motor unit pairs increased substantially based on being in the same finger compartments (McIsaac & Fuglevand, 2007). These findings are supportive of both an anatomical partitioning perspective as well as a task grouping perspective; the organization of this muscle appears to be related to anatomically divided compartments as well as supportive of different functional tasks to
which it contributes. In an investigation of single motor unit recruitment in the extensor carpi radialis (ECR) and extensor digitorum communis (EDC) muscles of humans during isometric wrist extension or radial deviation, ECR showed sized order recruitment but no task grouping. EDC, on the other hand, exhibited two task subpopulations, one for middle finger extension and the other for ring finger extension despite lacking specific contractions of these digits (Riek & Bawa, 1992). One key element of this study is that single motor units were studied in vivo in humans; in this way, the EMG had better resolution and may be more indicative of the level of organization being probed. Additionally, the findings may be more generalizable to real world function. It is unclear what element of this task was relevant in driving this differential recruitment, but it may relate to the control of fractionation of the digits, which may be evident in other skilled tasks that have high precision requirements.

Skill requirements of a motor task are often probed by attempting to operationalize task complexity as well. Investigations of task complexity and its relation to cortical activation are relatively prevalent, with peripheral surface EMG typically being used as a dependent measure. One research group used TMS to probe cortical excitability as it related to task complexity, and found increased EMG response (i.e. motor evoked potential) in FDI during isometric finger abduction vs. power grip (Datta, Harrison, & Stephens, 1989). Another study had disparate results, finding larger EMG responses in FDI during complex tasks (activation of several muscles) vs. simple tasks
Flament and colleagues’ TMS results were confirmed using single motor units for a subset of participants. In their discussion, the authors reviewed how their complex tasks (rotation, pincer grasp, power grasp) may be part of a more complex pattern of muscle synergies. The variability of corticospinal evoked responses speaks again to the potential task-related variability at the cortical level. The difference in these results of these two studies was most likely due to advances in TMS methodologies/experimental design in the second study. Although the results are contradictory, potentially due in part to difference in methodologies (especially with regards to EMG electrode placement), it again suggests task-related cortical mechanisms that may parallel those at the spinal cord. Organizational principles of the nervous system tend to be consistent across the neural axis.

In response to TMS of the primary cortex in healthy humans during different precision vs. power tasks, the motor responses (EMG) of both proximal and distal muscles (including the FDI) were task-dependent despite no change in the H reflex (Schieppati, Trompetto, & Abbruzzese, 1996). The authors attributed their findings to be related to the amount of precision or control required by the task.

Going along with this idea of task complexity and skill requirements, it appears as if some investigations have uncovered this phenomenon only by taxing the system, which is in effect how task complexity and skill are frequently operationalized in studies of the
cortex. In EMG studies focused on spinal cord motor control, this is typically probed using a fatigue protocol.

*Fatigue*

A final task factor to consider is fatigue. Inhomogeneous muscle activation during fatiguing contractions in humans has been an area of investigation utilizing surface EMG arrays. The FDI of healthy adults displayed unexpected variability in EMG activity during a fatiguing isometric protocol (Zijdewind et al., 1995). Near the end of the endurance test (Figure 12B, arrow), one site (EMG-1) showed an increase in EMG, whereas the other site (EMG-2) showed no change. These findings were cited earlier related to their support of activation related to synergistic activity of motor units within a muscle.
A previously cited study by this group also provided evidence for differential activation during a maximum pinch task, although there was no comparison condition as this was not the primary scientific question being addressed (Zijdewind et al., 1998).

The use of a multi-site surface EMG array to investigate motor unit recruitment patterns has been shown to be reproducible within and between participants by one group that is particularly interested in fatigue paradigms (Holtermann, Roeleveld, & Karlsson, 2005). During a fatiguing contraction of the upper trapezius in healthy humans, different

**Figure 12: Fatigue-related variability in human FDI**

(B) FDI EMG of one participant at 2 locations showing fatigue-related variability: at end of endurance test (row 3, arrow), EMG-1 increased (row 2) whereas EMG-2 showed no change; abduction force maintained throughout (row 1); location of recording sites reflect coordinate system shown in Figure 5 (Zijdewind et al., 1995).
locations within the upper trapezius muscle were inhomogenously activated (Holterman & Roeleveld, 2006). Recently these same investigators have used a surface EMG array (13 x 10 sites) on the distal biceps in healthy humans to investigate fatigue/tremor relationships in motor unit synchronization in a way in which intra-muscular EMG cannot (Holtermann, Gronlund, Karlsson, & Roeleveld, 2009).

Summary of Background

As is apparent from the literature review, task-related variations in muscle activation and motoneuron recruitment patterns have been frequently reported, and are deserving of a more systematic pursuit. Based on evidence to date, theories such as anatomical partitioning or ensemble theory are not able to entirely explain experimental results. Muscle regionalization has proved valuable in providing insight into this differential activation, but again does not provide an all-inclusive explanation. Convincing evidence of mechanisms of this differential activation include somatotopic organization, interneuronal biasing, and synergistic activity of motor units within a single muscle. Task group theory is the most convincing theoretical perspective to address this scientific question, as it encompasses the most salient features of the other perspectives and is still able to explain the results across almost all studies. What is not clear is how the nervous system defines task and exactly what drives this differential activation.
Our study aims to probe the potential for differential activation as well as the specific influence of two task factors, direction and end goal of a functional task, as measured by activation across locations in one muscle using a surface EMG array. This may allow us to make inferences related to the potential organizational anatomy of the spinal cord. This area is rich for investigation, and the FDI muscle is a prime candidate for an initial foundational study. The FDI is a relatively simple two headed muscle that has been studied extensively, responsible for simple uniplanar coordinative tasks (i.e. abduction, flexion), yet also involved in complex skilled functional tasks (i.e. grasp, pinch).

**Purpose of Proposed Study**

The purpose of the proposed study was to determine if there is task-related differential activation in the human FDI, and determine the effects of: i.) direction of movement in extrinsic space, and ii.) end goal of two functional tasks. Additionally, we aimed to determine if there is an anatomical pattern to this differential activation (i.e. proximal/distal or radial/ulnar).
Aims & Hypotheses

Our broad research goal was to gain insight into how the neuromuscular system is organized for movement, as studied at the level of a single human muscle and its motorneuron pool. More precisely, our goal was to determine if the muscle is differentially activated (as measured by a surface EMG array) in a task-specific manner, indicating a potential functional somatotopic organization. We aimed to elucidate the specific effect of two task factors on this organizational control: direction and end goal of the task, as well as any trends in the anatomical pattern of differential activation.

The specific aims & corresponding hypotheses were:

**Specific Aim #1:** Determine if there was within-session stability of M waves values as measured by comparison of mean peak-to-peak M waves per site and linearity between sites (6 comparisons total) during abduction MVC at the beginning of the directional tasks as compared to that measured during abduction MVC at the end of the directional tasks.

**Hypothesis 1 (H1):** i.) M waves during abduction MVC at the beginning and end of a session would not differ within site, and ii.) relationship across sites would not differ across time.
Specific Aim #2: Determine if there is inhomogeneous activation (mean peak integrated EMG; IEMG) in different locations of a single muscle (first dorsal interosseous; FDI) simultaneously during a given task as measured by a surface EMG array. A comparison of EMG was made: i.) in the same bipolar site during seven different tasks, and ii.) in four different bipolar sites during each of the tasks.

Hypothesis 2 (H2): activation would differ between sites during at least one task.

Specific Aim #3: Determine if the inhomogeneous activation, as measured by a comparison of mean peak IEMG, was related to directional requirements of the task.

Hypothesis 3 (H3): i.) activation across sites would differ within each of 3 directional tasks (abduction MVC, flexion MVC, diagonal MVC) as well as within site across directional tasks, and ii.) inhomogeneous activation across sites would be different after addition of a secondary directional movement in each of the combination tasks (30% abduction MVC + 30% flexion MVC, 30% flexion MVC + 30% abduction MVC).

Specific Aim #4: Determine if the inhomogeneous activation, as measured by comparison of mean peak IEMG across sites, was related to end goal of the functional task.

Hypothesis 4 (H4): there would be inhomogeneous activation across sites during both functional tasks.
**Specific Aim #5:** Determine if there was an anatomical pattern to the inhomogeneous activation (mean peak IEMG).

**Hypothesis 5 (H5):** i.) there would be different activation for the combined distal sites as compared to combined proximal sites, and ii.) for combined radial sites as compared to combined ulnar sites when combined across all tasks.

**Significance**

The significance of this scientific question is that it will lead to an enhanced understanding of organization and motor control at the muscle level and may provide clues as to organization at the spinal cord and motorneuronal pool level. At this point in time, it is unclear exactly what ramifications our findings may have clinically, although it is clear that a deeper understanding of this area will lead to a better grasp of central nervous system organization in general. This in turn will facilitate our understanding of movement, at some level, in both healthy models as well as those with pathology. Additionally it will most likely have ramifications related to the use and interpretation of surface EMG data in movement-related research studies in humans.

Clarification of task grouping at the muscle level and the influence of different task factors (i.e. movement direction, motor task/program) that affect motorneuron
recruitment may give us insight into the movement patterns we are observing in populations with pathology, i.e. abnormal synergies such as those observed post-stroke. After stroke, humans typically present with characteristic movement patterns, or synergist patterns; when attempting to carry out either an isolated single joint movement or a multi-joint coordinated task, certain unwanted movements arise. For example, when an individual post-stroke attempts to carry out a movement such as shoulder elevation, a common pattern observed in the upper extremity is shoulder retraction, depression, internal rotation, elbow flexion, forearm pronation, and wrist and finger flexion (Johnstone, 1978). Certain muscle groups are inadvertently activated during volitional movement, inhibiting coordinated control. Brunnstrom referred to a stereotyped sequence of stages during recovery post-stroke: 1.) flaccidity, 2.) basic components of synergies with some spasticity, 3.) some voluntary control of synergies with increased spasticity, 4.) movement out of synergies and decreased spasticity, 5.) synergies no longer have dominance over motor acts and increased coordinated movement, and 6.) movement coordination approaches normal (Brunnstrom, 1970).

These synergies are thought to be due to lack of cortical inhibition of motor neurons, and clarification of task grouping at the motorneuron level could possibly give insight into these patterns. The capability for plasticity of axons to find specified muscle targets (i.e. in a regionalized or task-specific manner) has been shown to be deteriorated in later life (Kernell, 1998). This may have implications for recovery after neurologic injury in
elderly individuals, and may in part explain some of these aberrant muscle synergies observed post-stroke. The results may shed light on masked synergies present in the undamaged nervous system as well as those post-stroke, which may at some point facilitate the development of rehabilitation techniques.

**Current Gaps**

Currently there is adequate evidence supporting this experimental question, yet considerable gaps that can be addressed. Some of the gaps in this area include: limited presentation/detailed methodology related to EMG (particularly in human models), no previous use of a surface EMG array to localize motorneuron recruitment patterns specifically related to this question, deficient number of systematic investigations probing different task factors/requirements that influence this inhomogeneous motorneuron pool/muscle activation, small sample sizes, and a paucity of literature that attempts to integrate findings on this topic across the neural axis. We attempted to address some of these gaps in our proposed study, namely reproduction of earlier findings of task-related variation in muscle activation/motorneuron recruitment patterns, and discrimination of the influence of two specific task factors related to this organizational principle.
Methods

Design

The proposed experiment used a two factor (site x task) repeated measures within subject design (Table 1). Task was carried out using the right index finger and had 7 levels: abduction maximum voluntary contraction (MVC), flexion MVC, 30% abduction + 30% flexion MVC, 30% flexion + 30% abduction MVC, diagonal MVC, power grasp MVC, and key pinch MVC. Site had 4 levels: distal radial, distal ulnar, proximal ulnar, and proximal radial (Figures 13a&b).

Table 1: Design: 2-way Repeated Measures ANOVA (task*site)
The independent variables were: i.) task, ii.) location within the surface EMG array (referred to as site; operationalized by 4 separate bipolar sites recording simultaneously), iii.) within session time point, and iv.) epoch of the combination tasks. The response variables were: i.) mean peak-to-peak M wave amplitude per site per task (during active contraction), and ii.) mean peak IEMG amplitude at each of the 4 electrode sites per task. We also attempted to control for and collect force values (see Instrumentation), but force was not a primary response variable.

Figure 13: Surface EMG array positioned on participant's hand
(a.) Anatomical references for EMG array.
(b.) 4 bipolar sites positioned at extremes of FDI muscle on array.
Participants

Participants were recruited from a sample of convenience through advertisements on campus (Recruitment Flyer in Appendices). The inclusion criteria were: right-handed (as determined by Oldfield Handedness Questionnaire; see Appendices) (Oldfield, 1971), between the ages of 18-45 years old (27 ± 7 y.o.; mean ± SD), no known orthopedic nor neurologic disorders affecting right hand movement or sensation, ability to receive peripheral electrical stimulation, ability to comprehend task instructions, ability to elicit M waves and obtain consistent surface EMG on all 4 sites, no known allergies to adhesive, and not currently a practicing musician. All participants were required to sign an informed consent as approved by the University of Minnesota Institutional Review Board (Informed Consent, see Appendices).

Based on our exploratory power analysis using mean peak IEMG as our primary outcome measure for a two-tailed paired t-test, we needed to enroll 26 participants to get a power of 0.80 with an alpha of 0.05. The IRB was written to approve up to 40 participants, with the plan for final inclusion/retention of 26 as based on our power analysis. We attempted to recruit an equal number of males and females, ending up using data from 7 males and 19 females.
Instrumentation

**EMG**

All EMG recordings were carried out over the right FDI muscle belly using a surface EMG array (Figures 13a&b). The skin was lightly abraded with sandpaper, and then cleaned with rubbing alcohol using towelettes. Within the surface array, four bipolar sites were utilized at the extremes of the muscle belly, based on each participant’s anthropometry. The first site was placed in the most distal radial, the second in the most distal ulnar, third in the most proximal radial, and fourth in the most proximal ulnar location of each participant’s FDI muscle (Figures 13a&b). The bipolar electrode recording sites were gold-plated receptacles (2 mm diameter) embedded in perforated Aquaplast splinting material (1/8” thickness), inter-electrode distance (center to center) was 4 mm. The array had 5 gold-plated receptacles along its width and 7 along its length, for a total of 35 receptacles within the array (Figure 13a&b). Matching gold-plated pins (Millmax, Oyster Bay, New York) were soldered to wire (<1 mm thick), which then connected to the array to 4 separate 5mm diameter pre-amplifiers (Therapeutics Unlimited, Iowa City, Iowa) that were adhered to a wooden mount to prevent movement (Figures 14a&b).
A reference circular dot adhesive electrode (4 cm diameter) (3M, St. Paul, Minnesota) was placed over the ulnar styloid process for all EMG measures. EMG was collected for two different variables: M waves and EMG during active contractions without nerve stimulation. The M waves were collected as described in Procedures, raw with a sampling rate of 10k, gain of 1k. The EMG during active contractions was collected with a sampling rate of 1k, and time constant of 55ms. It was later smoothed over a 100ms window and analyzed offline using Excel (Microsoft, Redmond, Washington). Acceptable EMG for both measures was initially verified by asking the
participant to abduct his/her index finger while ensuring that 4 sites recorded appropriately.

_Nerve Stimulation_

The electrical stimulation was applied with a bipolar surface stimulating electrode adhered to the participant’s ulnar groove, just proximal to the elbow joint, where the ulnar nerve is closest to the skin (Figure 15).

![Figure 15: Ulnar nerve stimulator](image)

Side view of participant in experimental set-up; blue neoprene wrap reinforcing adhered stimulating electrode at elbow.

A Grass S88 (Grass Technologies, West Warwick, Rhode Island) stimulator was
used to deliver constant current stimulation (Grass CCU constant current unit) through a stimulus isolation unit (Grass SIU isolation unit). The stimulus consisted of a 1.2 second train of 3 x 0.4 millisecond pulses and was collected during contractions for each of the 7 task conditions. Stimulus intensity was adjusted until the peak-to-peak M waves value did not increase; at that point, the intensity was increased by approximately 10% (within participant tolerance). This set intensity was maintained during collection of the M waves for all tasks throughout the duration of the experiment.

**Force**

Force was collected for index finger abduction and flexion during the directional tasks using 2 separate (Transducer Techniques, Temecula, California) 50 pound load cells suspended orthogonal to each other in the experimental set-up (Figures 16a & 16b).
For the pinch task, the participant held the load cell in his/her hand between the pad of the thumb and the lateral aspect of the 2\textsuperscript{nd} digit, in a key pinch position (Figure 17a). For the power grasp task, the load cell was placed in the grip of the dynamometer (Jamar Technologies, Hatfield, Pennsylvania) to capture grip force (Figure 17b). Force was sampled at 1000 Hz. The gain for the directional tasks was 1K, whereas it was 500 for both of the functional tasks to prevent saturation.

**Figure 16: 2 load cells measuring finger forces during directional tasks**
Top load cell measures index finger abduction force, side load cell measures flexion force (a.) participant’s view. (b.) lateral view.
Experimental Set-up & Procedures

The experiment was carried out on one day, requiring approximately 2-3 hours (Experimental Protocol & Data Collection Form, see Appendices). As per university institutional review board standards, the potential participant read the informed consent (see Appendices), and appropriateness as well as interest in inclusion in the experiments was determined by both the experimenter and the potential participant.

After signing the informed consent, the participant filled out two questionnaires: (i.) Oldfield Handedness Questionnaire (verbally probed by experimenter; see Appendices), and (ii.) a fatigue visual analog scale (Fatigue Scale, see Appendices). The handedness questionnaire was filled out once for each participant prior to the experiment, and the fatigue questionnaire was filled out twice, at the beginning and end of each
session.

The participant's skin over the FDI, midforearm and posterior elbow was cleaned using rubbing alcohol, and the area over the FDI was gently abraded using sandpaper. The choice of 4 bipolar sites was determined based on the anthropometry of each individual participant (Figures 18a-18f). First the angle between the first and second metacarpals was placed in the angle identical to that of the resting hand splint. With the hand in this position, a marker was used to mark the borders of the FDI: radial border of 2nd metacarpal, base where 1st & 2nd metacarpal approximate, ulnar border of the 1st metacarpal, and the horizontal connection of these two longitudinal borders as palpated by the most distal end of the FDI muscle.
The surface array was placed within these markings, aligning the ulnar lateral border of the array with the radial aspect of the 2nd metacarpal. The four most extreme bipolar sites that fit within the marked borders of the muscle were utilized for recording. The four most extreme bipolar recording sites per participant were determined based on the tracing: the most distal radial, distal ulnar, proximal ulnar, and proximal radial FDI locations. Once the optimal placement as well as the determination of the recording sites had been made, the plastic 1"x1" surface EMG electrode array was adhered to the participant's right FDI using Tegaderm first (3M, St. Paul, Minnesota), reinforced by Micropore (3M, St. Paul, Minnesota) tape (Figure 19) and remained there for the duration

Figure 18: Set-up of array based on anthropometry of participant
(a.) angle between 1st & 2nd metacarpal measured using goniometer while hand in resting splint  (b.) hand out of splint, same angle  (c.) borders of FDI marked (d.) array placed within borders as described in Procedures  (e.) array removed and 4 extreme sites on FDI selected for measurement  (f.) Example of different size hand and its effect on array sites.
of the experiment.

A bipolar stimulation electrode was adhered in the right ulnar groove using Micropore tape superficially, reinforced by a blue neoprene wrap (Figure 15). The participant's right hand was then placed in a plastic resting hand splint (Aquaplast) that stabilized all of the fingers except the index finger using hook and loop Velcro (Figure 20); this splint was removed during the two functional tasks. The participant sat on a supportive platform (hips and knees at approximately 90 degrees flexion), and rested his/her right arm in a comfortable position (approximately 60 degrees of shoulder flexion, neutral shoulder rotation, 60 degrees elbow flexion, midpronation, wrist neutral) with the hand supported in the experimental set-up through use of wooden supports at the wrist joint and the forearm. The index finger was surrounded above and to the left by thin plastic/PVC attached to two separate load cells, capable of measuring index finger
abduction and flexion force separately (see ‘Force’, Figure 16).

Prior to recording active contraction of each different experimental task, we systematically evoked the maximum output of the motorneuron pool (M waves) by external stimulation of the ulnar nerve x 3 repetitions (1 train of 3 pulses) during an active MVC contraction. As described earlier, we initiated stimulation at a low intensity, increasing incrementally until no further increase in the peak-to-peak M waves occurred with further increases in the stimulus intensity. This value is considered the maximum M wave. We then increased the intensity 10% (to participant tolerance) and kept the intensity at this level throughout the remainder of the experiment. The M waves for the abduction set-up were measured two times: at the beginning and end of the directional

Figure 20: Experimental set-up
(a.) Aquaplast splint on right hand to stabilize other fingers. (b.) side view of participant positioning within set-up.
tasks (during abduction MVC) as a test of within-session fatigue. The evoked peak-to-peak M wave values were utilized to normalize individual electrode array site EMG activity during the active test conditions in an attempt to control for any incongruities in surface contact, impedance, etc.

In total, 3 repetitions of 8 different active isometric hand/finger task conditions were carried out in a pseudo randomized order within certain experimental constraints: i.) 2 blocks of tasks [the directional tasks carried out within the abduction set-up (abduction MVC, flexion MVC, diagonal MVC, 30% abduction + 30% flexion, 30% flexion + 30% abduction), and the functional tasks outside off this set-up (key pinch MVC, power grasp MVC)], ii.) abduction MVC pre at the beginning and abduction MVC post at the end of the directional task block, and iii) both combination tasks were carried out in succession.

More specifically, the task conditions consisted of: index finger abduction MVC, index finger flexion MVC, index finger diagonal MVC, 30% finger abduction MVC + 30% flexion MVC, 30% finger flexion MVC + 30% abduction MVC, key pinch MVC, and power grasp MVC. During these tasks, we simultaneously collected surface EMG at 4 different sites within the electrode array as well as force data. As mentioned earlier, the force data was collected for both index finger abduction and flexion for all tasks except the 2 functional tasks (power grasp and key pinch). These tasks each had a somewhat separate set-up that attempted to emulate true functional tasks (isometrically) while
collecting 4 channels of EMG data as well as 1 channel of force using the previously mentioned set-ups.

The participants received a minimum of 3 practice trials for each task condition prior to data collection of that condition in an attempt to ensure comprehension and decrease the potential for learning effects during data collection. More than 3 practice trials were allowed if the participant's performance was inconsistent or he/she was unable to successfully perform the task. The participant received feedback of the force profiles online via the oscilloscope (Tektronix Inc, Beaverton, Oregon) during the contraction for all of the conditions. Participants were allowed rest breaks as needed, although we attempted to keep them stabilized in each task-specific set-up for the duration of the experiment (approximately 2-3 hours).

Each participant's MVC was measured for both index finger flexion and abduction separately; these values were recorded to ensure consistency, as well as used to calculate force percentages for the combination task conditions (e.g. 30% abduction + 30% flexion MVC and 30% flexion + 30% abduction MVC). MVCs were collected by asking the participant to contract upon verbal command to maximum isometric contraction (abduction or flexion), hold for approximately 4-5 seconds, then ramp back down to baseline/rest. Three repetitions were carried out for each of these tasks. As noted earlier, the average force values for these MVCs were utilized to calculate % MVCs for the combination conditions.
Two combination task conditions, 30% abduction +30% flexion MVC and 30% flexion + 30% abduction, were carried out in the same set-up as noted above. Verbal instructions were given, as was a visual aid (marked force targets on the oscilloscope screen), to initiate isometric contraction of the first movement (i.e. index finger abduction) at 30% MVC for 2 seconds, add in 30% MVC of the second movement (i.e. index finger flexion) while maintaining the first for 2 seconds, then incrementally drop out the second contraction, then drop out the first. The same number of practice trials and repetitions applied to these task conditions. The primary difference between the two combination task conditions was the order in which they were presented (i.e. abduction 1st or flexion 1st).

The diagonal task condition entailed the participant carrying out an isometric MVC contraction in the direction 45º degrees off of straight abduction and flexion, towards the direction of the corner in which the orthogonal load cells are suspended. The matched maximum values (MVC) for both forces attempted to control the force requirements of this task condition, in attempt to manipulate only directional requirements of the task.

The power grasp task was carried out with the upper arm and forearm supported as described earlier with slight variation from the set-up in the directional tasks (no hand splint, different wooden supports; Figure 17), with the hand grasping onto a Jamar dynamometer. The participant performed a power grasp MVC for 5 seconds x 3
repetitions. The load cell recorded the force on the scope. The key pinch task was carried out with the upper arm and forearm supported as described in the power grasp task (again no hand splint, different wooden supports), but the hand was somewhat "fisted" with the load cell placed between the lateral aspect of the proximal phalanx of the index finger and the pad of the thumb (Figure 17). The participant performed a key pinch MVC for 5 seconds x 3 repetitions; the force output was again measured by the load cell. Standardized verbal instructions for both functional tasks are included in the Appendices (Functional Task Instructions).

**Data Analysis**

**EMG**

*Data Analysis*: The response variables below were assessed for each task:

1.) Mean peak-to-peak M wave amplitude (during active contraction)

The mean peak-to-peak amplitude of the M waves across 3 repetitions for each bipolar site, each task condition, during one session were further used for statistical analysis.

2.) Mean peak IEMG amplitude at each of the 4 electrode sites per task
Each site’s rsEMG was smoothed (100ms window) and then normalized to its respective mean peak-to-peak M wave value for each task; after normalization, each was integrated (IEMG) across the time interval of the given task; the peak IEMG was then divided by 10,000 to make the arbitrary values manageable; the average peak IEMG of 3 trials was used for statistical analysis.

The data was collected online using a custom built Labview program (National Instruments Corporation, Austin, Texas), then exported into Excel 2007 (Microsoft, Redmond, Washington) for final analysis. Seven channels of data (4 EMG channels, 2 force channels, 1 nerve stimulation channel) were fed into the 16 bit A/D board (National Instruments Corporation, Austin, Texas). As noted earlier in the EMG section, the EMG data was amplified (1k for M waves, 10k for EMG during tasks). The EMG collected during the active conditions was full wave rectified with a time constant of 55ms. The raw exported M wave data was imported into Excel where the peak-to-peak averages were calculated. Figure 21 illustrates one repetition of raw M waves data during the abduction MVC task for one participant.
Figure 21: M wave data for 4 sites in array
Raw M wave data for 4 sites in array during abduction MVC task.

Figure 22 illustrates the peak-to-peak value of one M wave obtained from one repetition at one site during abduction MVC, which was later averaged across 3 repetitions, then used to normalize the active EMG data per task, per site.
The EMG during the active conditions was first exported into Excel, full wave rectified and smoothed (rsEMG), then normalized to the mean peak-to-peak M wave values for the corresponding site and task during that session (Figure 23).

**Figure 22: Peak-to-peak M wave for 1 site in array**

Peak-to-peak M waves data for 1 site during abduction MVC task.
These normalized rsEMG values were then integrated, the peak IEMG per site calculated, and then averaged across 3 repetitions to get the mean peak IEMG. For the two combination tasks, the mean peak IEMG of the first epoch was calculated (i.e. during initial flexion of the 30% flexion MVC + 30% abduction MVC) as was that of the second epoch (i.e. during the additional abduction phase of the same combination movement separately) (Figure 24).

Figure 23: Rectified smoothed EMG (rsEMG) for 4 sites in array
Single repetition of full wave rectified, smoothed EMG, normalized to average peak-to-peak M waves for each site during abduction MVC task for one participant.
The gains (noted in Procedures) as well as the necessary mathematical conversions for acceptable/conventional units for all dependent measures were adjusted once the data had been exported into Excel.

**Force**

Force data for both index finger abduction and flexion was collected for all tasks except power and pinch, which we only collected for one channel representing the overall force of interest (i.e. power grasp force or pinch force). This data was also exported into
Statistical Analysis

As noted in the Methods section, each participant participated in 48 measurements: 8 tasks x 6 repetitions (3 M waves, 3 MVCs). Statistical analysis was performed with SAS Institute Inc. software (Version 9.2, Cary, North Carolina).

Participants’ data was included in an analysis if there were 4 sites of measureable valid EMG (Table 2 in Appendices). The proposed experiment was a two factor (site x task)
within subject repeated measures design (Table 1). Twenty seven participants were tested, but only twenty six participants’ data were included in the analyses. One participant’s data was not analyzed due to her unusually high fatigue rating post (8.3/10 on VAS; 10 = maximum fatigue); we based this decision on the fact that our average fatigue rating post-session for all of our other participants was 2.34/10.

To examine differences in the primary response variable, EMG amplitude, we used a mixed model analysis with subject as a random effect and experimental factors (i.e. within session time point, site, task, epoch, and/or anatomical location) as fixed effects, plus a term for task order. The specific analyses are noted below. For all statistical measures, a $p < 0.05$ was considered to be significant. When appropriate, a Bonferonni adjustment was made for multiple comparisons with a family-wise error rate of $\alpha = 0.05$.

The hypotheses and corresponding statistical models are listed below.

**H1: Within Session Stability of M waves**

**Hypotheses:** i.) M waves during abduction MVC at the beginning and end of a session would not differ within site, and ii.) relationship across sites would not differ across time.

**Response:** mean peak-to-peak M waves

**Model:** Random effect: subject; fixed effects: site + time + site*time
- site at 4 levels (distal radial, distal ulnar, proximal ulnar, proximal radial)
- time at 2 levels (pre, post)

**H2: Inhomogeneous Activation Across Sites During All Tasks**

**Hypothesis:** activation would differ between sites during at least one task.

**Response:** mean peak IEMG

**Model:** Random effect: subject; fixed effects: site + task + site*task + order

- site at 4 levels (distal radial, distal ulnar, proximal ulnar, proximal radial)
- task at 7 levels (abduction, flexion, diagonal, 30% abduction + 30% flexion, 30% flexion + 30% abduction, power, pinch)
- order = 1 through 7

**H3: Influence of Direction on Inhomogeneous Activation**

**Hypotheses:** i.) activation across sites would differ within each of 3 directional tasks as well as across directional tasks, and ii.) inhomogeneous activation across sites would be different after addition of a secondary directional movement in the combination tasks.

**Response:** mean peak IEMG

**Models:** i.) Random effect: subject; fixed effects: site + task + site*task + order

- site at 4 levels (distal radial, distal ulnar, proximal ulnar, proximal radial)
• single directional task at 3 levels (abduction, flexion, diagonal)
• order = 1 through 3

ii.) Random effect: subject; fixed effects: site + epoch + site*epoch

• site at 4 levels (distal radial, distal ulnar, proximal ulnar, proximal radial)
• epoch at 2 levels (pre, post)

H4: Effect of End Goal of Functional Tasks

Hypothesis: i.) there would be inhomogeneous activation during both functional tasks.

Response: mean peak IEMG

Model: Random effect: subject; fixed effects: site + task + site*task + order

• site at 4 levels (distal radial, distal ulnar, proximal ulnar, proximal radial)
• task at 2 levels (power, pinch)
• order = 1, 2

H5: Anatomical Pattern of Inhomogeneous Activation

Hypothesis: i.) there would be different activation for the combined distal sites as compared to combined proximal sites, and ii.) for combined radial sites as compared to combined ulnar sites.
**Response:** mean peak IEMG

**Model:** Random effect: subject; fixed effects: proximal + radial + proximal*radial + task + task*proximal + task*radial + task*proximal*radial + order

- proximal at 2 levels (1=proximal, 0= distal)
- radial at 2 levels (1= radial, 0= ulnar)
- task (7 levels: abduction, flexion, diagonal, 30% abduction + 30% flexion, 30% flexion + 30% abduction, power, pinch)
- order = 1 through 7

**Results**

The experimental results are presented as adjusted means with the range (lower level – upper level) of the 68% confidence interval (adjusted mean ± 1 standard error), in the order of the previously noted hypotheses, with corresponding data for each hypothesis. As noted in *Methods*, the final IEMG is unitless due to normalization to the M wave. All data sets were log transformed due to non-normality [see hypothesis-specific residual plots (Figures 43, 45, 47, 49, 51, 53, 55, 58, 59 in *Appendices*)] with the exception of the post-hoc analysis on force, which was normally distributed. SAS output in the *Appendices* contain log values, whereas data presented in the *Results* section text and graphs have been transformed back to unit values. Models were run as noted in the
Statistical Analyses section; as per the notes below, if a factor (i.e. order) or interaction (i.e. site*time) was not significant, the model was reset excluding that factor. If an interaction was significant, on the other hand, it was split up based on the specific interaction (according to convention) and re-run.

H1: Within Session Stability of M waves

Hypotheses: i.) M waves during abduction MVC at the beginning and end of a session would not differ within site, and ii.) relationship across sites would not differ across time.

This hypothesis was fully supported. Figure 26 demonstrates in a representative participant that the M waves remained stable within an experimental session (pre vs. post).
Means across participants confirmed that the M waves across sites as well as the difference between times remained stable within session, as shown by no significant interaction of site*time ($p = 0.9231$; Figure 27; Figure 44 in Appendices). The model was then re-run without the interaction term.

**Figure 26: Within session M waves across sites for a single participant**
Data from a single participant during abduction MVC (a.) pre & (b.) post demonstrating within session stability; each value represents the average peak-to-peak M waves from 3 stimuli.
Therefore two pieces of evidence support of M wave reliability within session: i.) no significant interaction of site and time, indicating that the relationship across sites was maintained within session, and ii.) no significant main effect of time ($p = 0.6964$) between average peak-to-peak M waves during abduction MVC from pre (mean = 2.88, CI: 2.65-3.14 mV) to post (mean = 2.96, CI: 2.71-3.22 mV). One additional finding to note (since the MVC EMG was normalized to the M waves) was that mean M wave at
the distal radial site was significantly greater than the distal ulnar and proximal radial sites ($p = 0.0500$).

**H2: Inhomogeneous Activation Across Sites During All Tasks**

**Hypothesis:** activation would differ between sites during at least one task.

This hypothesis was fully supported. Figures 28 a, b & c depict single participant data illustrating inhomogeneous activation across FDI sites (greater mean peak IEMG in distal ulnar site as compared to other 3 sites) during three of representative tasks, as well as different amplitudes across tasks.
Single trial (rsEMG on left, IEMG on right) for 3 different tasks: (a.) diagonal MVC. (b.) flexion MVC. (c.) 30% flexion + 30% abduction MVC from a single participant demonstrating inhomogeneous activation; > IEMG in distal ulnar site as compared to 3 other sites; different amplitudes across sites based on task.

**Figure 28: IEMG across sites for 3 different tasks for a single participant**

Single trial (rsEMG on left, IEMG on right) for 3 different tasks: (a.) diagonal MVC. (b.) flexion MVC. (c.) 30% flexion + 30% abduction MVC from a single participant demonstrating inhomogeneous activation; > IEMG in distal ulnar site as compared to 3 other sites; different amplitudes across sites based on task.
There was not a significant interaction of task*site when all tasks (Table 3 in Appendices) were analyzed together ($p = 0.9958$; Figure 29; Figure 46 in Appendices), nor an order effect. Order and interaction were then dropped and the model was re-run. Evidence of inhomogeneous activation was shown by: i.) a significant main effect of site ($p < 0.0001$) and task ($p < 0.0001$). The distal ulnar site had significantly greater ($p < 0.0001$) IEMG than all 3 other sites (mean = 3.53; 68% CI = 3.31-3.76; distal radial mean = 2.09; 68% CI = 1.96-2.23; proximal ulnar mean = 1.64; 68% CI = 1.54-1.75; proximal radial mean = 1.79; 68% CI = 1.68-1.91); the distal radial site had greater activation ($p < 0.0500$) than the two proximal sites. Related to tasks, the diagonal MVC (mean = 2.84; 68% CI = 2.66-3.04), abduction MVC (mean = 2.65; 68% CI = 2.47-2.83), and power MVC (mean = 2.65; 68% CI = 2.47-2.83) had significantly greater ($p < 0.0500$) mean peak IEMG than the other tasks; the pinch task (mean = 2.06; 68% CI = 1.93-2.21) had greater ($p < 0.0500$) IEMG than both combination tasks (30% abduction + 30% flexion mean = 1.75; 68% CI = 1.63-1.87; 30% flexion + 30% abduction mean = 1.70; 68% CI = 1.59-1.82).
H3: Influence of Direction on Inhomogeneous Activation

**Hypotheses:** i.) activation across sites would differ within each directional task as well as across directional tasks, and ii.) inhomogeneous activation across sites would be different after addition of a secondary directional movement in the combination tasks.
1. Comparison Across Directional Tasks

This hypothesis was partially supported. To make comparisons across tasks, a subset of three tasks (abduction vs. flexion vs. diagonal) each with different directional requirements was analyzed. Figures 30 a, b & c demonstrate greater mean peak IEMG in a single participant during diagonal and abduction as compared to flexion; additionally note the different patterns in IEMG amplitude across sites for each task (i.e. diagonal & abduction appear to have greater activation in the distal radial site as compared to flexion).
A significant interaction was present (p = .03) due to the inconsistent ordering of a single trial from one participant during 3 directional tasks (rsEMG on left, IEMG on right): (a.) diagonal MVC. (b.) abduction MVC. (c.) flexion MVC; > IEMG during diagonal and abduction; different amplitudes across sites for each task (diagonal & abduction appear to have greater distal ulnar activation as compared to flexion).

Figure 30: IEMG across sites during 3 directional tasks for a single participant

Single trial from one participant during 3 directional tasks (rsEMG on left, IEMG on right): (a.) diagonal MVC. (b.) abduction MVC. (c.) flexion MVC; > IEMG during diagonal and abduction; different amplitudes across sites for each task (diagonal & abduction appear to have greater distal ulnar activation as compared to flexion).
A significant interaction was not present for site*task ($p = 0.9196$; Figure 31; Figures 48 in Appendices) in this subset of directional tasks, nor was there an order effect; both were dropped from the model and it was re-run. Related to the main effect of task ($p < 0.0001$), when all sites were combined, diagonal MVC (mean = 2.84; 68% CI = 2.66-3.04) and abduction MVC (mean = 2.62; 68% CI = 2.45-2.80) were both significantly greater ($p < 0.0001$) than flexion MVC (mean = 1.80; 68% CI = 1.68-1.92). When all three directional tasks were combined, again the distal ulnar site mean peak IEMG (mean = 3.93 arbitrary units; 68% CI = 3.67-4.20) was significantly greater than all other sites (distal radial mean = 2.31; 68% CI = 2.16-2.47; proximal ulnar mean = 1.77, 68% CI = 1.65-1.89, proximal radial mean = 1.98, 68% CI = 1.85-2.12), demonstrating a main effect of site ($p < 0.0001$). The distal radial site was also significantly greater than both proximal sites ($p < 0.0500$).
This hypothesis was partially supported. The second approach to analysis of the influence of direction on inhomogeneous activation entailed carrying out 2 separate analyses (1 for each combination task). We used the combination tasks to determine how the relationship across sites changed when a second directional movement requirement was added; both combination tasks had the same movements (abduction and flexion), but the movements were presented in an opposite order.

Figure 31: IEMG across sites during 3 directional tasks for group data

Group mean IEMG demonstrating no interaction of site*task \((p = 0.9196)\); significantly > mean peak IEMG during diagonal & abduction MVCs as compared to flexion at all sites \((p < 0.0001)\). > IEMG at distal ulnar site for all three tasks \((p < 0.0001)\); > activation in distal radial site than both proximal sites \((p < 0.0500)\).

2. Different Epochs of Combination Tasks

This hypothesis was partially supported. The second approach to analysis of the influence of direction on inhomogeneous activation entailed carrying out 2 separate analyses (1 for each combination task). We used the combination tasks to determine how the relationship across sites changed when a second directional movement requirement was added; both combination tasks had the same movements (abduction and flexion), but the movements were presented in an opposite order.
30% Abduction + 30% Flexion MVC Combination Task

Figure 32 illustrates single participant data showing that the relationship across sites appears to remain relatively unchanged after addition of the 2\textsuperscript{nd} directional requirement. Additionally, there is greater activation in the distal ulnar site throughout the duration of the task, and greater IEMG in all sites during the second epoch (due to the additive nature of integrating across time).
Figure 32: IEMG & force during 30% abduction + 30% flexion MVC for a single participant
(a.) Single participant data (rsEMG on left, IEMG on right) illustrating relatively little change in EMG across sites after addition of a 2nd directional requirement; distal ulnar site with greatest IEMG. (b.) force profile illustrating abduction and flexion forces during trial.

Figure 33 depicts these same findings in the group mean peak IEMG data, with no significant interaction of site*epoch in this combination task for the group data ($p = 0.9460$; Figures 50 in Appendices), indicating no change in relationship across sites over time. The interaction term was dropped out and the model was re-run.
For this combination task there was a main effect of site ($p < 0.0001$) as per previous analyses, whereby the distal ulnar site had significantly greater activation than all three other sites ($p < 0.0001$); both radial sites had greater activation than the proximal ulnar site ($p < 0.0500$). As expected based on the integrative function, there was a main effect of epoch ($p < 0.0001$) whereby post IEMG (mean = 1.78, 68% CI = 1.62-1.95) was significantly greater ($p < 0.0001$) than pre (mean = 0.51, 68% CI = 0.46-0.56).
30% Flexion + 30% Abduction MVC Combination Task

The 2nd combination task, 30% flexion + 30% abduction MVC was analyzed as per below. Single participant data in Figure 34 demonstrates greater peak IEMG in the distal ulnar site, which is further increased during the second epoch (i.e. post) of this combination task; the EMG across sites during the first epoch differs than that present during the second epoch. In this way, the relationship of the IEMG across sites is not maintained after addition of a secondary directional requirement (abduction).
The most notable finding in this analysis was a significant interaction of site*epoch ($p = 0.0063$; Figure 35; Figure 52 in Appendices), indicating that the relationship across sites was not maintained after addition of the secondary directional requirement (abduction). Based on this interaction, the data was stratified by epoch and further analyzed based on each subgroup; the main effect of site ($p < 0.0001$) present in each epoch differed. During the “pre” epoch, the only difference across sites was that the

**Figure 34: IEMG & force during 30% flexion + 30% abduction MVC for a single participant**

(a.) Single participant data (rsEMG on left, IEMG on right) illustrating a change in EMG across sites after addition of a 2nd directional requirement; distal ulnar site with greatest IEMG. (b.) Force profile illustrating abduction and flexion forces during trial.
distal ulnar site (mean = 0.39, 68% CI = 0.34-0.44) was significantly greater ($p < 0.0500$) than the proximal ulnar site (mean = 0.27, 68% CI = 0.24-0.31). During the “post” epoch (after addition of abduction), however, the distal ulnar site (mean = 2.73, 68% CI = 2.47-3.02) was greater ($p < 0.0001$) than all three other sites (distal radial mean = 1.69, 68% CI = 1.53-1.87; proximal ulnar mean = 1.32, 68% CI = 1.19-1.46; proximal radial mean = 1.49, 68% CI = 1.35-1.65). Additionally, the distal radial site was greater than the proximal ulnar site ($p < 0.0500$). As expected based integration of data, all sites’ IEMG increased during the second epoch (main effect of time; $p < 0.0001$).

**Figure 35: IEMG during 2 epochs of 30% flexion + 30% abduction MVC for group data**

Group data illustrating an interaction between site*epoch ($p = 0.0063$), supportive of an altered IEMG relationship across sites after addition of the secondary direction; distal ulnar site significantly greater ($p < 0.0001$) than all other sites only during the 2nd epoch; post distal radial > proximal ulnar site ($p < 0.0500$).
In summary, for both combination tasks, the addition of a secondary force only led to a different EMG relationship across sites in the second combination condition, 30% flexion + 30% abduction MVC, related to the addition of abduction. Again, the only difference in the two tasks theoretically was the order in which the directions were carried out.

**H4: Effect of End Goal of Functional Tasks**

**Hypothesis:** i.) there would be inhomogeneous activation during both functional tasks.

This hypothesis was fully supported. Figure 36 is of single participant data demonstrating greater peak IEMG during the power (as compared to pinch) as well as greatest IEMG in the distal ulnar site.
There was inhomogeneous activation that was different when comparing the two functional tasks. Mean group data is shown in Figure 37, demonstrating no significant interaction between site*task ($p = 0.8542$; Figure 54 in Appendices); interaction and order (insignificant effects) were removed and the model was re-run. Related to the main effect of functional task, the mean power IEMG was significantly greater ($p < 0.0001$;
mean = 2.64, 68% CI = 2.44-2.87) than pinch MVC (mean = 2.06, 68% CI = 1.90-2.24). Consistent with our previously noted results, when combined across functional tasks, this inhomogeneous activation differed across sites, as seen by a significant main effect of site ($p < 0.0001$); the distal ulnar site had significantly greater ($p < 0.0001$) mean peak IEMG (3.86, 68% CI = 3.53-4.20) across both functional tasks than all other sites (distal radial = 2.25, 68% CI = 2.06-2.45; proximal ulnar = 1.86, 68% CI = 1.71-2.03; proximal radial = 1.84, 68% CI = 1.69-2.00). The distal radial site had greater activation than both proximal sites ($p < 0.0500$).
Figure 37: IEMG during functional tasks for group data
Group data demonstrating an insignificant interaction between task*site ($p = 0.8542$); significantly greater activation in power task ($p < 0.0001$); significantly greater activation in distal ulnar site ($p < 0.0001$) for both tasks; greater activation in distal radial vs. both proximal sites ($p < 0.0500$).

H5: Anatomical Pattern of Inhomogeneous Activation

**Hypothesis:** i.) there would be different activation for the combined distal sites as compared to combined proximal sites, and ii.) for combined radial sites as compared to combined ulnar sites.

This hypothesis was fully supported. The single participant data graphed in Figure 38 shows greater peak IEMG in the distal ulnar site for both the power and the
diagonal MVC as compared to all other sites.

To assess if there was an anatomical pattern to the inhomogeneous activation, initially we ran a 3 way analysis (task*proximal/distal location*radial/ulnar location). Order, task*proximal, task*radial, and task*proximal*radial were all nonsignificant (Figures 39a, 39b, 39c, respectively; $p > 0.0005$); all of these were then dropped from the
model.
Figure 39: IEMG based on anatomical location for group data

Group data showing lack of significant interactions: (a.) task*proximal*radial location ($p = 0.9390$)  (b.) task*proximal location ($p = 0.9222$)  c.) task*radial location ($p = 0.8866$)
There was a significant interaction of proximal*radial location ($p < 0.0001$; Figure 56 in *Appendices*). Due to the significant interaction, the data were then stratified by proximal/distal location and further analyzed based on each subgroup (Figures 40a & 40b); additionally the data were stratified by radial/ulnar location and further analyzed based on each subgroup (Figure 41a & 41b).

1. **Proximal vs. Distal Comparison**

For the proximal sites (Figure 40a), there was a main effect of radial/ulnar location (Table 2; $p = 0.0109$) such that there was greater activity in the proximal radial site as compared to in the proximal ulnar site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Peak IEMG (68% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal Ulnar</td>
<td>1.64 (1.54-1.75)</td>
</tr>
<tr>
<td>Proximal Radial</td>
<td>1.79 (1.68-1.91)</td>
</tr>
</tbody>
</table>

For the proximal sites there was also a main effect of task (Table 3; $p < 0.0001$) such that diagonal, power, and abduction tasks had greater activation ($p < 0.0500$) than all other tasks.
For the distal sites (Figure 40b), again there was a main effect of radial location (Table 4; \( p < 0.0001 \)) such that there was greater activation (\( p < 0.0001 \)) in the distal ulnar site than in the distal radial site.

**Table 4: Comparison of Distal Sites Based on Site**

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Peak IEMG (68% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distal Ulnar</td>
<td>3.53 (3.30-3.78)</td>
</tr>
<tr>
<td>Distal Radial</td>
<td>2.09 (1.95-2.24)</td>
</tr>
</tbody>
</table>

There was also the same main effect of task (Table 5; \( p < 0.0001 \)) for the distal sites such that diagonal, power, and abduction tasks had greater activation (\( p < 0.0500 \)) than all other tasks (flexion, pinch, 30% abduction + 30% flexion, 30% flexion + 30% abduction).
2. Radial vs. Ulnar Comparison

For the radial sites (Figure 41a), there was a main effect of proximal/distal location (Table 6; \( p < 0.0001 \)) such that there was greater activity in the distal radial site.
as compared to in the proximal radial site.

**Table 6: Comparison of Radial Sites Based on Site**

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Peak IEMG (68% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distal Radial</td>
<td>2.09 (1.97-2.23)</td>
</tr>
<tr>
<td>Proximal Radial</td>
<td>1.80 (1.69-1.91)</td>
</tr>
</tbody>
</table>

For the radial sites there was also a main effect of task ($p < 0.0001$) such that diagonal, power, and abduction tasks had greater activation ($p < 0.0500$) than all other tasks (flexion, pinch, 30% abduction + 30% flexion, 30% flexion + 30% abduction).

**Table 7: Comparison of Radial Sites Based on Task**

<table>
<thead>
<tr>
<th>Task</th>
<th>Mean Peak IEMG (68% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>abduction</td>
<td>2.41 (2.25-2.59)</td>
</tr>
<tr>
<td>flexion</td>
<td>1.61 (1.50-1.73)</td>
</tr>
<tr>
<td>diagonal</td>
<td>2.55 (2.38-2.74)</td>
</tr>
<tr>
<td>30% abduction + 30% flexion</td>
<td>1.62 (1.50-1.74)</td>
</tr>
<tr>
<td>30% flexion + 30% abduction</td>
<td>1.56 (1.45-1.68)</td>
</tr>
<tr>
<td>power</td>
<td>2.28 (2.12-2.46)</td>
</tr>
<tr>
<td>pinch</td>
<td>1.80 (1.68-1.94)</td>
</tr>
</tbody>
</table>
For the ulnar sites (Figure 41b), again there was a main effect of proximal/distal location (Table 8; \( p < 0.0001 \)) such that there was greater activation in the distal ulnar site than in the proximal ulnar site.

![Figure 41: IEMG at radial vs. ulnar sites for group data](image)

Group IEMG (a.) comparison of both radial sites with > IEMG at distal site \( (p < 0.0001) \) (b.) comparison of both ulnar sites with > activation at distal site \( (p < 0.0001) \).

Table 8: Comparison of Ulnar Sites Based on Site

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Peak IEMG (68% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distal Ulnar</td>
<td>3.53 (3.30-3.77)</td>
</tr>
<tr>
<td>Proximal Ulnar</td>
<td>1.64 (1.54-1.75)</td>
</tr>
</tbody>
</table>

There was also a main effect of task (Table 9; \( p < 0.0001 \)) for the ulnar sites such that diagonal, power, and abduction tasks had greater activation \( (p < 0.0500) \) than flexion and both combination tasks. What was a little different with this analysis compared to the
one stratified by proximal/distal location was that only diagonal and power were greater
\((p < 0.0500)\) than pinch, and pinch was greater than 30% flexion + 30% abduction \((p <
0.0259)\).

**Table 9: Comparison of Ulnar Sites Based on Task**

<table>
<thead>
<tr>
<th>Task</th>
<th>Mean Peak IEMG (68% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>abduction</td>
<td>2.91 (2.69-3.14)</td>
</tr>
<tr>
<td>flexion</td>
<td>2.00 (1.85-2.16)</td>
</tr>
<tr>
<td>diagonal</td>
<td>3.16 (2.93-3.42)</td>
</tr>
<tr>
<td>30% abduction + 30% flexion</td>
<td>1.90 (1.75-2.06)</td>
</tr>
<tr>
<td>30% flexion + 30% abduction</td>
<td>1.86 (1.71-2.01)</td>
</tr>
<tr>
<td>power</td>
<td>3.06 (2.82-3.31)</td>
</tr>
<tr>
<td>pinch</td>
<td>2.36 (2.18-2.55)</td>
</tr>
</tbody>
</table>

In summary, there was evidence of inhomogeneous activation based on
anatomical locations: greater activation proximally in the radial site and distally in the
ulnar site; with regards to radial sites, greater activation distally, and ulnar sites also had
greater activation distally.

**Additional Post Hoc Analyses**

1. **Within Session Abduction Force (Pre vs. Post)**

To probe the potential for fatigue, which would be an undesirable side effect
potentially affecting EMG, we did a one-way repeated measures ANOVA of the force
data during abduction MVC with independent factor of within session time point (2 levels: abduction MVC pre and post), and response variable of mean maximum force. As noted earlier, the force data was normal and did not need to be log transformed (Figure 58 in *Appendices*). Figure 42 demonstrates single participant data (a. & b.) and mean group data (c.) showing a significant decrease in force ($p = 0.0041$) from pre (mean $= 23.06$, 68% CI = 21.58-24.54 Newtons) to post (mean $= 20.35$, 68% CI = 18.83-21.86 Newtons).
2. **Within Session Abduction IEMG (Pre vs. Post)**

We also collected IEMG during both abduction MVC pre and post to further probe this question of potential fatigue. There was no significant interaction of time*site...
(Figure 60 in Appendixes; $p = 0.8366$), so this factor was dropped out and the model was re-run. As illustrated in single participant data (Figure 43a, 43b) and group data (Figure 43c), there was no significant difference in mean peak IEMG within session (no main effect of time; $p = 0.6703$; mean pre = 2.64, 68% CI = 2.46-2.85; mean post = 2.61, 68% CI = 2.42-2.81). There was a main effect of site ($p < 0.0001$) whereby the distal ulnar site had the greatest activation.
Figure 43: Within session IEMG during abduction MVC

Single participant (a. & b.) and group (c.) data illustrating no significant difference in mean peak IEMG within session during abduction (insignificant interaction time*site; \( p = 0.6703 \)).
Discussion

Key Findings

Our primary finding was that a single human muscle, the first dorsal interosseous (FDI), was differentially activated (as measured by a surface EMG array) in a task-specific manner. We found inhomogeneous activation in different locations of the FDI simultaneously during all of the tasks we investigated. Our data support the idea that motorneuron pools are not uniformly activated for all motor programs; movements may therefore be associated with the action of the parts of the muscle-tendon complex. We specifically probed the: i.) influence of movement direction in extrinsic space, ii.) influence of end goal of two functional tasks, and iii.) possibility of an anatomical pattern to the differential activation. This finding of task-based differential activation across sites of a single muscle and expands upon previous evidence in both animal and human models (Hensbergen & Kernell, 1992; Hoffer et al., 1987; McIsaac & Fuglevand, 2007; O'Donovan et al., 1982; Riek & Bawa, 1992; Tax et al., 1990; ter Haar Romeny et al., 1982; ter Haar Romeny et al., 1984; Zijdewind et al., 1998; Holtermann, Roeleveld, & Karlsson, 2005).

Related to the influence of movement direction in extrinsic space, we found that the pattern of differential activation across sites (i.e. difference in amplitude between
each site) was not exactly the same for each different movement direction (i.e. abduction and flexion; Figure 31). Additionally, certain directional tasks (abduction & diagonal) had greater activation when collapsed across all sites as compared to other tasks (flexion) despite the fact that all three were maximal contractions. This lends support to the idea that not only is there differential activation across sites in general during directionally based tasks, but also confirms that the differential activation varies based on direction of movement in extrinsic space. This is consistent with findings by ter Haar Romeny in the human biceps during elbow flexion vs. forearm supination vs. shoulder external rotation (ter Haar Romeny et al., 1982; ter Haar Romeny et al., 1984). Their group found localized activation (motor unit threshold for activation) that related to these three separate movements, which interestingly, could be considered movements in 3 different planes in extrinsic space. Our findings are not consistent with those of Thomas’ group using needle EMG in FDI during flexion, abduction and pinch(Thomas et al., 1986). This may be due to the fact that they were unable to record from 30% of the motor units, and some of these units may have been preferentially activated based on direction. The discrepancy in results between studies may also be due to differences in the following: anatomical locations of recording sites, force levels, set-up (no hand splint allowing contribution of other hand muscles), and/or task (hold steady, not ballistic). They also had a sample size of only 4 participants.

More interestingly, when we probed the effect of starting with a certain
directional movement and adding a second directional requirement (combination tasks), we found that addition of the secondary direction only had an effect in the 30% flexion + 30% abduction task. The movement requirements (i.e. direction and force as % MVC) were essentially the same during the 2^nd^ epoch of both combination tasks. This unique finding during the one combination task may be attributed to one of four factors: i.) importance of order of directional tasks, ii.) importance of abduction direction in this movement, iii.) influence of task complexity, or iv.) familiarity/use of the index finger for certain directional combinations more than others. Ter Haar Romeny had a similar finding seemingly related to order of supination and flexion using needle EMG: activation depended upon a linear combination of movements (ter Haar Romeny et al., 1982; ter Haar Romeny et al., 1984). Zijdewind et al. also found differential activation as a function of inadvertent addition of a secondary direction (flexion) during a fatiguing isometric abduction task, reiterating the influence of combinations of directional movements (Zijdewind et al., 1995), not necessarily the abduction movement. As noted earlier, complexity, operationalized differently in many different experimental tasks, has also been shown to influence differential activation as measured by EM (Datta et al., 1989; D. Flament, P. Goldsmith, C. J. Buckley, & R. N. Lemon, 1993; D. Flament, P. Goldsmith, C.J. Buckley, & R.N. Lemon, 1993; McIsaac & Fuglevand, 2007; Riek & Bawa, 1992; Romaiguere et al., 1989).

Our results related to the influence of end goal of a functional task support the
premise that end goal does indeed influence activation, although we are not clear at this point the relationship between the two. We found greater activation overall during the power task as compared to the pinch task. The pattern across EMG sites or locations between these two functional tasks appeared to be the same (also indicated by no interaction; Figures 36 & 37), although the distal ulnar site appeared to have a disproportionate increase during the power task as compared to the pinch task. Greater activation was illustrated primarily by greater IEMG amplitude across all sites overall during the power task, although it is likely that other muscles play a role in the force generation as well. Based on the fact that EMG has been shown to correlate relatively closely with force, this finding could possibly be attributed to the higher force levels during that task. What needs to be considered related to the ‘end goal’ results is the potential for unmonitored EMG in synergistic muscles during these tasks. Based on anatomy and function, one might expect very similar activation for the abduction and power tasks (> greater abduction component for both), or the flexion and pinch tasks (> flexion components for both, possibly > activation of flexor digitorum profundus); this was not the case.

Our exploration of anatomical patterns of differential activation led to some interesting yet complicated results. Our data does support some sort of anatomical organization in activation peripherally, namely greatest activation for all participants during all tasks at the distal ulnar site. This is consistent with the greater activation seen
in a similar FDI location during a fatiguing FDI contraction in a previous study (Zijdewind et al., 1995). Due to the statistical interactions, we needed to parse up the sites in a manner that may or may not be consistent with the way in which the nervous system is controlled, potentially an artificial division. Regardless, after analyzing the data based on two different submodels (distal vs. proximal, radial vs. ulnar), we did find differential activation related to the anatomical location of the recording site. When we divided the four sites into distal vs. proximal sites, distal activation was greater in the ulnar site (69% greater; Table 4), and proximal activation was greater radially (9% greater; Table 2). This is interesting because the connection of these two sites appears to follow the pennation angle of the bulk of the superficial head of the FDI muscle. What must be considered, as evident in Figure 40, is that although statistically significant, the difference between the two proximal sites numerically was actually relatively small.

When we partitioned the site based on radial versus ulnar locations, we found that there was greater activation distally for both radial (16% greater; Table 6) and ulnar (115% greater; Table 8) sites. This is of interest because of previous work (primarily in the cat) that has shown anterior/posterior, proximal/distal, and exterior/interior (depth) peripheral activation patterns that matched the rostrocaudal organization centrally in the spinal cord (Hoffer et al., 1987; Romanes, 1951; Swett et al., 1970; Wang & Kernell, 1998; Wang & Kernell, 2000; Wang & Kernell, 2002). Again, though, we must remember that the difference in both radial sites, although statistically significant, was
small in comparison. The fact that our two sub analyses didn’t lead to clearly defined consistent results make it difficult to interpret them as a whole. As discussed in the Neurophysiologic Perspective section, we have gone on to make inferences of potential spinal cord organization based on these anatomical patterns (Figure 48). Again, the most outstanding finding related to anatomy was that the distal ulnar site always had the greatest activation.

Of interest, but unrelated to our specific hypothesis, we found that the M wave values appeared to differ: i.) across sites in general, ii.) during active vs. passive conditions, iii.) across participants, and iv.) across tasks. As the M wave is thought to be the maximum output of the muscle, this is an area that may lead to interesting future explorations specifically investigating the M wave. We attribute these differences to variations in surface contact of the electrodes during different tasks. Since the M wave relationship across sites did not directly inversely parallel the relationship of the EMG recordings across sites during active contractions (Figure 44), the validity of our findings is strengthened. Therefore the differential activation must not be merely an artifact of recording site differences (i.e. contact, resistance, etc.), but is a real phenomenon.
M waves & corresponding IEMG (3 trial ave & SD) for one participant during (a.) abduction (b.) pinch & (c.) power. Nonparallel site differences across the M wave & IEMG validate the differential activation.
Potential Explanations/Interpretation

Task group theory is the theoretical foundation from which our experiment was designed. Although we are unsure how the nervous system views a “task”, we approached the interpretation of our results from three different perspectives: i.) anatomic/biomechanical, ii.) neurophysiologic, and iii.) a systems functional perspective. Clearly these perspectives are not independent of each other, but we felt the interpretation would be more manageable using this approach. The differential activation across sites was not exactly the same for every task, which may be a product of any of these three perspectives.

Anatomic/Biomechanical Perspective

Consideration of the architectural features of the system as well as biomechanical constraints is necessary for a thorough exploration of our results as it likely provides insight into functional properties of a muscle. The FDI is a two headed muscle with a superficial and a deep head (Figure 45) (Infantolino & Challis, 2010; Masquelet et al., 1986). As a whole, the muscle attaches distally (inserts) into to the palmar plate of the metacarpophalangeal joint, the lateral tubercle of the base of the proximal phalanx of the index finger, and the interosseous hood (Masquelet et al., 1986). The fibers of the
superficial head typically dominate/cover those of the deep head. The origin of the superficial head, which has helical twisted fibers, is the medial surface of the 1st metacarpal bone; the origin of the deep head is the lateral, palmar surface of the 2nd metacarpal. The two heads come together mid-web space, and both heads are innervated by the ulnar nerve (Masquelet et al., 1986). The pennation angles of the two heads are different in orientation, but are not significantly different in value (Infantolino & Challis, 2010). The pennation angle of the bulk of the muscle (i.e. superficial head) runs in a distal ulnar direction, whereas a smaller seemingly separate portion of the muscle (i.e. distal head) runs in a distal radial direction. The FDI has one of the largest physiologic cross-sectional areas (PCSA) of the hand muscles, (1.50 ± 0.40 cm²) with an average fiber length of 31.7 ± 2.8 mm and pennation angle of 9.2± 2.6 degrees (Jacobson et al., 1992). Since PCSA is proportional to maximal tension, the FDI must be designed in part for strong isometric forces. Based on the ratio of fiber length to muscle length, which was the lowest in FDI of all the intrinsic hand muscles, this muscle may not be as well designed for excursion. Studies that have attempted to characterize FDI architecture have reported a large amount of variability for all architectural parameters, which they interpreted as meaning that function can not necessarily be deduced directly from anatomy for this muscle (Infantolino & Challis, 2010; Johnson, Polgar, Weightman, & Appleton, 1973).
When the index finger is extended (as our participants were instructed to do for all directional tasks), the superficial head abducts the first digit, with a smaller group of fibers attached to the proximal part of the proximal phalanx having a flexion moment. The superficial head also causes slight pronation of the distal index finger, as used in key pinch (Masquelet et al., 1986). Based on its anatomy and electrophysiologic evidence, the deep head is more responsible for flexion of the proximal phalanx (Masquelet et al., 1986). This head of the muscle also comes into play with stronger opposition contractions. Based on their findings combining anatomy and EMG, Masquelet’s group proposed that the superficial head has mainly a phasic function while the deep head is

**Figure 45: Anatomy of FDI**
Anatomy of FDI illustrating (1) interosseous hood (2) Metacarpophalangeal fibrous girdle (3) deep head of FDI (4) superficial head of FDI (5) lumbrical (6) radial wing of extensor aponeurosis (Masquelet et al., 1986)
used more for posture/stability.

For our discussion, we have explored index finger abduction movement assuming the locations of the 4 bipolar electrodes below (both radial sites on the superficial head, both ulnar sites on the deep head (Figures 46a & 46b). Again we are not sure of the exact location of each of our bipolar sites, so we must speculate.

Figure 46: FDI anatomy and 4 bipolar recording sites (adapted from Masquelet et al., 1986)
FDI anatomy (Masquelet et al., 1986) (a.) with superimposed assumed locations of the 4 bipolar recording sites (red dots): 2 radial sites on superficial head, 2 ulnar sites on deep head. (b.) participant’s hand illustrating demarcation of corresponding bipolar sites.

Based on pennation angle/orientation alone, both heads of the FDI should not exert their force in the same direction. It is possible that the deep head functions as more
of a stabilizer for the larger superficial head, pulling on the retinaculum so that the larger compartment has something stable from which to generate more force. As Kernell suggested (Kernell, 1992), this may allow production of stable, gradable force.

Based on our speculated recording site locations, the moment arm of the distal ulnar site (Figure 47) would be shorter than that of the moment arm of the distal radial site. Therefore the distal ulnar site would require more force to generate the same abduction torque, which is one explanation for the greater activation under the distal ulnar site.
Muscle fiber type distribution in the FDI, with relation to the muscle regionalization theory mentioned in Background, consists of relatively equal mean Type I (57.4%; tonic) and Type II (42.6%; phasic) fibers with less evidence of fiber type grouping in the muscle, wide variation in fiber type proportions across specimens, similar Type I & type II diameters, and large Type II fibers in general (Johnson et al., 1973; J. Polgar, M. A. Johnson, D. Weightman, & D. Appleton, 1973). In this way, lack of

Figure 47: Schematic of FDI moment arms for abduction MVC based on 2 bipolar sites

Schematic of FDI (adapted from (Masquelet, Salama, Outrequin, Serrault, & Chevrel, 1986) depicting axis of rotation for abduction (blue dot), 2 bipolar recording sites (red dots) and corresponding moment arms. Moment arm for distal ulnar site (purple dashed line) is shorter than that of distal radial site (green dashed line) therefore requiring greater force to generate same abduction torque. This may have led to greater activation under this site.
domination by a certain fiber type and lack of distinct fiber type regionalization do not explain nor necessarily elucidate our results.

As is evident, our results do not appear to be fully explained using an anatomical nor biomechanical approach. Despite the fact that neural organization and anatomy peripherally generally coincide, anatomy alone does not explain the differential activation we found. This is consistent with ter Haar Romeny’s work cited earlier in which exclusive supination muscles units were active medially vs. flexion units laterally in the long head of the biceps muscle, despite common wrist torques (ter Haar Romeny et al., 1982). Other studies have similarly supported the idea that anatomy alone (i.e. common tendon or muscle line of pull) is unable fully account for the inhomogeneous activation (English & Letbetter, 1982; O'Donovan et al., 1982). Stuart’s group summed it up well, saying “architectural features alone will never reveal the versatility of arrangements and mechanisms for operation of the segmental motor-control system” (p.444) (Stuart et al., 1988)

Neurophysiologic Perspective

When viewing our results from more of a neurophysiologic perspective, a few
things need to be considered: i.) gradients of interneuronal biasing onto different parts of the motorneuron pool, and ii.) synaptic regionalization of input from the motorneuron pool onto different regions of the muscle.

Regardless of location of motor unit types within the FDI, differential motor unit recruitment that has been driven by different linear combinations of task directions has been seen in motor units within a single muscle (O'Donovan et al., 1982; ter Haar Romeny et al., 1982; ter Haar Romeny et al., 1984; Zijdewind et al., 1995). One goal of ours was to make meaningful inferences regarding the anatomical organization of the human spinal cord related to these peripheral patterns, particularly to the potential for a functional somatotopic organization centrally. Based on previous literature (Hensbergen & Kernell, 1992; Hoffer et al., 1987; Romanes, 1951; Swett et al., 1970), the peripheral activation/topography may relate to task groups corresponding with intraspinal somatotopic organization. Spinal interneurons may be the key driving force to this organization. Below is a schematic of a potential model of central organization based on our findings (Figure 48; adapted from ideas in Kernell, 1992). What this figure illustrates (bigger picture on left, zoomed in components on right) is a descending task-based command which is conveyed to interneurons at the spinal cord level. Certain interneurons have greater impact on the FDI motorneuron pool (noted by thicker arrow). These spinal interneuronal inputs bias certain components of the pool based on task (i.e.
part of pool for abduction vs. different part of pool for pinch). Specific motor neurons from the FDI motorneuron pool then differentially bias different locations within the FDI muscle peripherally, noted by thicker arrows specifically targeting the distal ulnar site of the FDI.
Although we did not directly measure interneuronal inputs, we believe that the

Figure 48: Schematic of potential organization of FDI motorneuron pool
Potential organization of FDI motorneuron pool based on a larger gradient of input from intraspinal interneurons, as well as greater input from a given motorneuron in the FDI motorneuron pool onto the distal ulnar site as compared to other FDI locations (adapted from ideas presented in Kernell, 1992); thicker arrows = > biasing.
differential activation present in our results must be due to both interneuronal biasing as well as synaptic regionalization of the FDI motor neuron pool in the spinal cord.

**Systems Functional Perspective**

We would be remiss if we fail to address this task-related differential activation without viewing the nervous system from a bigger picture perspective, as it may relate to function. It is possible that our results support a much larger organizational scheme whereby the FDI activation is somehow incorporated into multi-muscular motor programs or synergies present in everyday tasks (Cope et al., 1996; Kernell, 1992; Riek & Bawa, 1992; Weiss & Flanders, 2004).

Another bigger picture perspective is that since we did not probe cortical excitability, we are completely unsure of the cortical involvement in this differential activation. It is possible that the EMG we measured may be the same at certain sites peripherally, but central drive onto the spinal cord (from descending inputs) may actually have been different; we did not measure this.

**Benefits of This Organizational Schema**

Traditionally movement has been associated with the action of the whole muscle-
tendon complex. As noted earlier, the nervous system needs to solve many different types of movement “problems”. Based on this need for efficiency, it makes sense to view its organization more from a functional perspective as opposed to a purely anatomical one. This perspective would allow the system to solve specific task requirements, beyond the neuroanatomy of the participating structures. It does not make sense, nor is it consistent with what we currently know about other levels of the neural axis such as the cortex (Flanders, 2005; Kernell, 1992; Weiss & Flanders, 2004), that the periphery (i.e. the muscle in this case) would be non-specialized and completely redundant in its functional properties. Additionally we know that the principle of topographical organization is ubiquitous throughout the nervous system (Flanders, 2005; Windhorst, 1996), supporting the premise that is would be so in the spinal cord as well.

Differential recruitment of motor unit populations in regions of whole muscle during different movements would facilitate recruitment of appropriate groups of muscles, or in the case of a single muscle, appropriate motor units for the task at hand (Weiss & Flanders, 2004). Motoneuron recruitment patterns could be appropriately flexible related to task allowing adjustability in force, speed, and endurance (Kernell, 1992). A certain task may require muscle coordination such that different distributions of activity are present within individual motoneuron pools. For these reasons, it makes sense that the nervous system at the level of the motoneuron pool would be organized in a task group fashion.
Significance of Findings

The most significant aspect of our findings is that they may lead to an altered view of how the muscle is controlled, a sort of paradigm shift. To our knowledge, our study was the first investigation of the direct effect of systematically manipulating these specific task requirements and objectively comparing muscle activation in a single muscle in humans in vivo via a surface EMG array. Based on the differential activation across sites of the FDI that was robust across participants, we have shown that the potential for the motor unit to be task group organized is, in the least, conceivable. Our findings were strengthened by our unique use of normalization to M waves, which further validated that the differential activation was indeed not just a recording artifact.

Our findings of differential activation across sites of a single human muscle has significant implications with regards to our overall understanding of motor control at the spinal cord level, contributing to our general understanding of motor control in a healthy human model. The results may potentially shed light on mechanisms underlying muscle fiber differentiation and motorneuron properties (Kernell, 1998). The differential activation observed peripherally may mirror the somatotopic organization at the cord level, which casts doubt on the traditional view of homogeneous organization of the motorneuron pool. As such, we can now begin to make inferences regarding the potential
anatomical organization of the human spinal cord related to the peripheral activation patterns we saw, and possibly gain some insight into the influence of the specific task factors. Although it is difficult to clearly interpret exactly which task factors drive this differential activation in vivo in humans, we have established a preliminary base of evidence from which future work can expand.

Additional contributions of our work that are a little more peripheral to central nervous system organization include: i.) reiterating the importance of precise surface EMG location placement in research (particularly TMS studies using FDI), and ii.) offering a unique approach to investigation of EMG using normalization by the M wave.

In addition to the scientific significance our results have, there are potential clinical implications. As described in the Background section, it is possible that these results may help explain some of the underlying synergies present in both the healthy nervous system and evident in those who have experiences neurologic injury. If the organization of the spinal interneurons centrally is somatotopically task grouped, an injury there (or above this level in the nervous system), may produce abnormal movement synergies we commonly see after stroke or traumatic brain injury. Lack of selective activation of motoneurons post-stroke has been correlated with decreased ability to fractionate isolated finger movements and associated reactions in gait. The abnormal activation in the motoneuron pool post-stroke supports our proposed organizational schema of task grouping.
Potential Alternative Explanations

It is possible that the fact that the distal ulnar site was closer to the innervation zone of the FDI muscle led to differential activation in this location unrelated to task group organization of the motorneuron pool (Saitou, Masuda, Michikami, Kojima, & Okada, 2000).

We were limited to four bipolar sites, and chose to measure in participant-specific anatomical extremes of the FDI. It is entirely possible that the organization may occur spatially in different areas that we did not explore. It is also possible that differences in force across tasks may explain the differential activation. There is a possibility that some of our recording sites (distal radial, distal ulnar, proximal radial) were placed over one head of the muscle whereas the other sites (proximal ulnar) may have been over the other head, in which case anatomy may have played a bigger role than we suspect. We are unable to determine this because we did not do concomitant imaging of any sort.

Since we did not have the instrumentation to simultaneously measure other hand muscles, we have limited ability to make inferences regarding how activation of other synergistic hand muscles may have impacted our results. It is possible that the activation of different muscles (i.e. long finger flexors) may explain this differential activation, particularly because the index finger was extended during the directional tasks.
Potential Limitations

One of the primary limitations of our work was the limited resolution of surface EMG as compared to fine wire or needle EMG for the type of research question we were asking. Although fine wire and/or needle EMG may have led to greater resolution (motor unit action potentials as well as potentially a 3rd dimension related to depth), we purposely decided to utilize surface EMG because it is: i.) painless and noninvasive, ii.) more reproducible related to spatial locations of sites within FDI across participants, iii.) allows one to capture the activity of more motor units (may be more representative), iv.) use of small diameter electrodes with small interelectrode distance allowed the specificity necessary to answer this preliminary question.

Based on the fact that our surface EMG array consisted of gold-plated receptacles and pins, there may have been some contamination of the signal, as gold may be less conductive which are more polarizable and capacitive, potentially leading to greater noise/movement artifact (Merletti, Botter, Troiano, Merlo, & Minetto, 2009). Additionally there may have been variable resistance across each of the four bipolar sites, but both of these potential limitations were held constant across participants, and we attempted to control for any recording concerns by normalizing to the M wave.

The fact that our participants were rather homogeneous, gathered from a sample
of convenience, with the end result being primarily healthy, young, active individuals, may be a limitation related to lack of generalizability. On the other hand, it may be a strength in that it was a controlled subgroup of the population, which was appropriate for a preliminary study such as ours.

Another consideration is that it is possible that we may not have picked the most influential task parameters/requirements based on how the nervous system actually defines a “task.” The generalizability of our tasks to real-world tasks may also be limited based on the fact that they were all isometric, and primarily maximum voluntary contractions. It is also very possible that we missed some differential activation that is actually present in submaximal contractions. One other methodological limitation may include unmeasured crosstalk from other hand muscles.

Future Directions

Future studies could best build upon our work in a few ways. One simple experiment that would build upon our results could use fine wire or needle EMG in 2 recording sites in the distal ulnar location of the first dorsal interosseous. The first site would remain constant, and the second location would be systematically varied (initially close to the first recording site, moved away incrementally with recordings at each distance). The temporal correspondence of the firing of the two single motor units
(recording site two relative to site one) could be recorded during isometric index finger abduction and flexion systematically investigated at different force levels (i.e. 30% MVC, 50% MVC, 75% MVC). This may be more sensitive to differential recruitment across locations in a given muscle.

Another different way in which we could build upon our findings would be by investigating the same question using a much larger surface EMG array (i.e. 135 bipolar sites). Other logical extensions of this study could also investigate: i.) manipulation of different task parameters (i.e. speed or position), ii.) submaximal force levels, and iii.) tasks that aren’t isometric. Other related work may explore the same parameters in different muscles and/or these same tasks measuring the FDI within the context of a multi-muscular synergy (i.e. simultaneously measure FDI, abductor digiti minimi and finger flexors during grasp). To probe the cortical contribution to the activation as well as the influence of different inputs on the interneuronal pools, transcranial magnetic stimulation could be utilized and compared to a peripheral stimulation. Because this study was very preliminary, there are many potential future investigative possibilities.

**Conclusions**

Task grouping exists in the human FDI muscle in humans. There are task-related variations across locations of the muscle that cannot be explained by anatomy alone.
organization of the nervous system at the level of the motorneuron pool is not necessarily an “all-or-none” phenomenon. Muscles are not simply homogenous units, activating in an all-or-none fashion during a motor task, but rather there is non-uniformity of motorneuron pool activation during a given task. It is unclear at this point in time how the nervous system defines task, and exactly how, as well as which tasks factors influence this differential activation. The exact role of spinal interneurons in biasing different aspects of the motorneuron pool vs. the role of differential input from the motorneurons onto different compartments of a given muscle is unclear at this point in time.
Bibliography


Holtermann, A., & Roeleveld, K. (2006). EMG amplitude distribution changes over the upper trapezius muscle are similar in sustained and ramp contractions. *Acta...


Appendices

Recruitment Flyer

Research Participants Invited

Finger Muscle Activation During Different Tasks

The Physical Therapy Program at the University of Minnesota is conducting a study to investigate how different parts of an index finger muscle activate simultaneously during different tasks.

Healthy right-handed adult volunteers between the ages of 18 and 64 without a history of orthopedic or neurologic problems that impair their ability to use their right index finger are invited to participate.

For more information please contact:
Maureen Whitford
Tel: 612-626-2443
whitf026@umn.edu
Consent Form

CONSENT FORM

Task-Related Variations in the Surface EMG of Human First Dorsal Interosseous Muscle

You are invited to be in a research study concerned with how different parts of an index finger muscle activate simultaneously during different tasks. This research will be carried out by a doctoral student, Maureen Whitford, under the advisement of Dr. Carl Kukulka, PhD, PT. Dr. Kukulka is on faculty in the Program of Physical Therapy within the Department of Physical Medicine and Rehabilitation at the University of Minnesota. You are selected as a potential participant because you responded to the announcement of the study. We ask that you read this form (or we can read it to you if you prefer) and ask any questions you may have before agreeing to be in the study.

Background Information:

The purpose of this study is to examine how different parts an index finger muscle are simultaneously active during different tasks (i.e. finger movement upwards or inwards, diagonally, pinching, & grasping). In addition, we will be assessing how the muscle activation changes with different directional requirements and goals of the task. In doing this experiment we are hoping to better understand how different tasks influence simultaneous activation in a single hand muscle. In the future this may help us gain a better understanding of how the spinal cord controls movement.

Procedure:

If you agree to be in this study, we would ask you to do the following:

- You will need to attend 1 experimental session that will take approximately 2-3 hours of your time. A few of the first 4-5 participants will be invited back for a second 2-3 hour visit so we can look at our ability to repeat the experiment consistently.
- Provide background information to the investigator about handedness and any history of orthopedic or neurological disorders that affect your ability to use your
right hand or receive peripheral stimulation, estimated amount of use/typical tasks you use your right hand for on an everyday basis, and fatigue prior to and after the experiment. These areas will be probed verbally by the investigator and/or by completing a questionnaire.

- Have a small (1”x1”) plastic electrode adhered to the web space of your right hand through use of medical adhesive tape. Additionally, you will have a second metal reference electrode taped to your mid forearm, and a third stimulating electrode taped to the back of your elbow. All three of these will be non-invasive (i.e. only on surface of skin, no needles).
- During the experiment, you will be seated with your right hand placed supported on a wooden table and secured by wooden uprights to prevent any movement of the arm during the tasks.
- Allow us to secure a stimulating electrode to the back of the right elbow (as noted above). The stimulus intensity will be adjusted until we reach a certain level of muscle activity, usually causing a slight muscle twitch. This may be slightly uncomfortable, but the intensity will be adjusted to ensure it is neither painful nor injurious to you. The stimulus will remain at this intensity throughout the experiment, administered systematically at specific times during certain tasks. Again, the sensation should be a mild tingling, and not painful. If the stimulation is uncomfortable, you should tell the researchers and you can stop participation.
- You will be asked to carry out 6 different tasks involving your right index finger/hand while sitting and in the experimental set-up. You will be asked to isometrically contract for <3 seconds for each task. 3 repetitions will be carried out for each of the 6 task conditions, for a grand total of 18 repetitions on your part.
- During some tasks you will be asked to simply contract your index finger in a specific direction as strong as possible for a brief period of time. In another task condition, you will be asked to contract your index finger in one direction to a certain level (as shown on a screen) and then add in a certain level contraction (again shown on screen) of the same finger in a different direction. Yet another condition will ask you contract your index finger maximally in a diagonal direction. Two other task conditions will ask you to either pinch or make a power grasp as strong as possible for a brief period.
- As noted above, during each task condition (i.e. pinch or moving finger up isometrically), we will stimulate at your elbow while you are in the task set-up. We will do this 9 times during each task condition, for a total of 54 brief stimulations (9 repetitions x 6 tasks).

**Risks and Benefits of Being in the Study:**
The study has minimal risks: first, the nerve stimulation requires us to use an electrical device that delivers a pulse to the nerve. As with any electrical devices applied to the skin, there is a remote possibility of an inadvertent electrical shock due to equipment malfunction. This risk is considered to be extremely remote in that safety mechanisms have been built into the device to eliminate such a problem. Second, the electric stimulator is capable of delivering very strong pulse of current. We will only use low intensities of stimulation that should feel like tingling with a slight muscle twitch in your hand. If the stimulus feels painful, you should inform us and the experiment will be stopped immediately. Other remote risks may include: allergic reaction to adhesive tape, mild soreness of the hand muscles for 1-2 days afterwards, slight discomfort from set-up and fatigue. Again, if any of these occur, we will address the issues promptly. There are no anticipated direct benefits to being in this study, but hopefully the knowledge gain will benefit our overall understanding of movement.

Alternatives to Participating in this Study:

This study does not incorporate any treatment and therefore you may either volunteer to participate or choose not to participate.

Research Related Injury:

In the event that this research activity results in any injury, treatment will be available, including first aid, emergency treatment, and follow-up care as needed. Care for such injuries will be billed in the ordinary manner, to you or your insurance company. If you think you have suffered a research-related injury, let the study investigator know right away.

Confidentiality:

The records of this study will be kept private. In any sort of report we may publish, we will not include any information that will make it possible to identify a subject.

Voluntary Nature of the Study:

Your decision whether or not to participate will not affect your current or future relations with the University nor the investigator(s). If you decide to participate, you
are free to withdraw at any time without affecting those relationships.

Contacts and Questions:

The researcher conducting this study is Maureen Whitford, PT, under the advisement of Carl G. Kukulka, PT, PhD. You may ask any questions you have now. If you have questions later, you may contact either of us at the Program in Physical Therapy, Box 388 MMC, The University of Minnesota, Minneapolis, MN 55455. Our phone contact is: (612) 625-0522.

If you have any questions or concerns regarding the study and would like to talk to someone other than the researcher(s), you are encouraged to contact the Research Subjects’ Advocate Line, D528 Mayo, 420 Delaware Street SE, Minneapolis, MN, 55455. Their phone contact is: (612) 625-1650.

You will be given a copy of this form to keep for your records.

Statement of Consent:

I have read the above information. I have asked questions and received answers. I consent to participate in the study.

Name_______________________________________________ Age__________

Signature____________________________________________

Date_________________

Name of Investigator___________________________________

Signature of Investigator________________________________

Date_______________
Oldfield Handedness Questionnaire

Participant ID: ______________________
Date: ___________

Edinburgh Handedness Inventory

Indicate your preference in the use of hands
++ = The preference is so strong that you would never try to use the other hand unless absolutely forced.
+ = Your preference in use of hand.
If you are truly indifferent, put a + in both columns.
Leave blank if you have no experience in that activity.

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<tr>
<td>15</td>
<td>Broom (upper hand)</td>
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<td>16</td>
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<td>17</td>
<td>Striking Match (match)</td>
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<td>18</td>
<td>Opening box (lid)</td>
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</tr>
<tr>
<td>19</td>
<td>Dealing card (card being dealt)</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Threading needle (needle or thread, according to which is moved.)</td>
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Total:
Fatigue Scale

on a scale from 0 to 10, please rate your fatigue

0 10

*scale minimized to fit formatting for thesis (VAS line actually 10cm long)
Experimental Protocol

**PROTOCOL FOR TASK GROUP EXPERIMENT**

1. Set-up of apparatus
   a. Change cables
   b. Connections for force and EMG
   c. Adjust settings at amplifier board
   d. Turn on/set-up:
      i. 2 scopes
      1. Set-up #2 on each
      ii. Stimulator- check settings, try on myself
      iii. Computer
      1. Pull up Labview (10k and 1k protocols)

2. Participant preparation
   a. Consent/review of experiment
   b. Sit within set-up
   c. Put on splint and adjust ht of set-up as needed; remove splint
   d. Skin prep
   e. Adhere electrode array
      i. Tegaderm
      ii. Micropore tape
   f. Stimulator probe
      i. Micropore and Transpore tape
   g. Put on splint again
   h. Hand in set-up, standardize UE position and adjust clamps

3. Data Collection (see data collection form)
   a. 4 sites within array
   b. Blocked order across participants
Functional Task Instructions

Grip:

“I want you to hold the handle like this and squeeze as hard as you can.”
**DEMONSTRATE**
“Are you ready? Squeeze as hard as you can.”
“Harder!...Harder!...Relax”

Pinch

“I want you to place your thumb on top of your index finger below as I am doing and pinch as hard as you can.”
**DEMONSTRATE**
Are you ready? Pinch as hard as you can.”
“Harder!...Harder!...Relax”

(Mathiowetz, Weber, Volland, & Kashman, 1984)
### Table 10: Table of Missing Data

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<td>Flexion MVC</td>
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<td>Power MVC</td>
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### Summary

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<td>10 participants with some missing data</td>
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SAS Output

*H1: Within Session Stability of M waves*

**Figure 49: M wave residuals and subsequent log transform**

M wave residuals before (a.) and after (b.) log transform. Log transformed data used for analysis due to non-normality.
Figure 50: Interaction plot for within session M waves

Interaction plot (adjusted mean ± 68% CI) of M waves pre (time 1) vs. post (time 2) across sites (1-4 on x-axis) during abduction MVC illustrating no interaction site*time ($p = 0.9231$).
**H2: Inhomogeneous Activation Across Sites During All Tasks**

**Figure 51: All task IEMG residuals and subsequent log transform**

IEMG residuals for all tasks before (a.) and after (b.) log transform. Log transformed data used for analysis due to non-normality.
Figure 52: Interaction plot for IEMG for all tasks across sites

Interaction plot (adjusted mean ± 68% CI) of IEMG across sites for all tasks (1-7 on x-axis) illustrating no interaction site*task ($p = 0.9958$)
Table 11: IEMG Across Sites for All Tasks

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<th>Distal Radial</th>
<th>Distal Ulnar</th>
<th>Proximal Ulnar</th>
<th>Proximal Radial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abduction</td>
<td>2.58(2.34-2.83)</td>
<td>4.48(4.07-4.92)</td>
<td>1.86(1.69-2.04)</td>
<td>2.20(2.00-2.42)</td>
</tr>
<tr>
<td>Flexion</td>
<td>1.77(1.61-1.93)</td>
<td>2.92(2.67-3.20)</td>
<td>1.43(1.30-1.57)</td>
<td>1.55(1.41-1.70)</td>
</tr>
<tr>
<td>Diagonal</td>
<td>2.80(2.56-3.07)</td>
<td>4.78(4.37-5.22)</td>
<td>2.14(1.96-2.34)</td>
<td>2.37(2.17-2.60)</td>
</tr>
<tr>
<td>30% Abd + 30% Flex</td>
<td>1.67(1.52-1.83)</td>
<td>2.80(2.55-3.08)</td>
<td>1.30(1.18-1.43)</td>
<td>1.54(1.40-1.69)</td>
</tr>
<tr>
<td>30% Flex + 30% Abd</td>
<td>1.66(1.51-1.82)</td>
<td>2.67(2.44-2.93)</td>
<td>1.29(1.17-1.41)</td>
<td>1.46(1.33-1.60)</td>
</tr>
<tr>
<td>Power</td>
<td>2.55(2.32-2.79)</td>
<td>4.46(4.06-4.89)</td>
<td>2.06(1.88-2.26)</td>
<td>2.04(1.86-2.24)</td>
</tr>
<tr>
<td>Pinch</td>
<td>1.95(1.79-2.14)</td>
<td>3.30(3.01-3.61)</td>
<td>1.66(1.52-1.82)</td>
<td>1.64(1.50-1.79)</td>
</tr>
</tbody>
</table>

**H3: Influence of Direction on Inhomogeneous Activation**

1. **Comparison Across Directional Tasks**
Figure 53: Directional task IEMG residuals and subsequent log transform

IEMG residuals for 3 directional tasks (abduction, flexion, diagonal) before (a.) and after (b.) log transform. Log transformed data used for analysis due to non-normality.
Figure 54: Interaction plot for IEMG across sites for 3 directional tasks

Interaction plot (adjusted mean ± 68% CI) of IEMG across tasks (abduction=1, flexion =2, diagonal=3) across sites (1-4 on x-axis) during abduction MVC illustrating no interaction site*time ($p = 0.9196$).
2. Different Epochs of Combination Tasks

30% Abduction + 30% Flexion MVC Combination Task

Figure 55: IEMG residuals and subsequent log transformation for 30% abduction + 30% flexion MVC

IEMG residuals for 30% abduction + 30% flexion MVC before (a.) and after (b.) log transform. Log transformed data used for analysis due to non-normality.
Interaction plot (adjusted mean ± 68% CI) of IEMG during 2 epochs (time 1=1st direction, time 2 = addition of 2nd direction) across sites (1-4 on x-axis) illustrating no site*time interaction ($p = 0.9460$).

30% Flexion + 30% Abduction MVC Combination Task
Figure 57: IEMG residuals and subsequent log transform for 30% flexion + 30% abduction MVC

IEMG residuals for 30% flexion + 30% abduction MVC before (a.) and after (b.) log transform. Log transformed data used for analysis due to non-normality.
Figure 58: Interaction plot during 2 epochs of 30% flexion + 30% abduction MVC

Interaction plot (adjusted mean ± 68% CI) of IEMG during 2 epochs (time 1=1\textsuperscript{st} direction, time 2 = addition of 2\textsuperscript{nd} direction) across sites (1-4 on x-axis) illustrating a significant site*time interaction ($p = 0.0063$).
H4: Effect of End Goal of Functional Tasks

Figure 59: IEMG residuals and subsequent log transformation for functional tasks

IEMG residuals for functional tasks (power, pinch) before (a.) and after (b.) log transform. Log transformed data used for analysis due to non-normality.
Figure 60: Interaction plot for functional tasks

Interaction plot (adjusted mean ± 68% CI) of IEMG during functional tasks (6=power, 7=pinch) across sites (1-4 on x-axis) illustrating no significant site*time interaction ($p = 0.8542$).
**H5: Anatomical Pattern of Inhomogeneous Activation**

Figure 61: IEMG residuals and subsequent log transformation for data based on anatomical location

IEMG residuals for all tasks based on anatomical location before (a.) and after (b.) log transform. Log transformed data used for analysis due to non-normality.
Figure 62: Interaction plot for data based on anatomical location

Interaction plot (adjusted mean ± 68% CI) of IEMG during all tasks based on anatomical location (0=ulnar, 1=radial) across other locations (0=distal, 1=proximal on x-axis) illustrating a significant proximal*radial interaction ($p < 0.0001$).
Additional Post Hoc Analyses

1. Within Session Abduction Force (Pre vs. Post)

Figure 63: Residuals for abduction force data

Force residuals during abduction pre and post illustrating normality; no log transform
2. Within Session Abduction IEMG (Pre vs. Post)

Figure 64: IEMG residuals and subsequent log transformation during abduction MVC
IEMG residuals for abduction MVC pre & post based before (a.) and after (b.) log transform. Log transformed data used for analysis due to non-normality.
Figure 65: Interaction plot for IEMG data during abduction pre vs. post

Interaction plot (adjusted mean ± 68% CI) of IEMG during abduction pre & post (x-axis time 1=pre, 2=post) across sites (1=distal radial, 2=distal radial, 3=proximal ulnar, 4=proximal radial) illustrating no significant proximal*radial interaction ($p = 0.8366$).