ABSTRACT

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SENSORY FEEDBACK MODULATES
MAXIMUM VOLUNTARY FORCE IN
MULTI-FINGER PRESSING

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The human hand is an excellent example of an effector capable of producing a wide range of forces for everyday manipulation tasks such as pressing, grasping and rotating objects. Both maximal and sub-maximal forces are essential for dexterous manipulation, and sensory feedback plays a critical role in successful completion of such tasks. While the role of sensory feedback in conducting sub-maximal force production has been a topic of extensive research, little is known about how sensory feedback affects the maximum voluntary force (MVF) and the multi-digit interactions (MDI) by the digits of the hand. The purpose of this study was to investigate the effect of cutaneous and visual feedback on MVF and MDI. The dissertation investigates five specific aims through five corresponding experiments. The first three specific aims investigate the effect of cutaneous feedback while the last two specific aims investigate the effect of visual feedback on MVF and MDI: specific aim 1 investigates the effect of digital anesthesia; specific aim 2 investigates the effect of transcutaneous electrical nerve stimulation (TENS); specific aim 3 investigates the effect of texture of the pressing surface; specific aim 4 investigates the effect of real-time visual feedback of digit forces; specific aim 5 investigates the effect of ambient light intensity. Young, healthy, right-handed subjects without any history of neurological disorders participated in the experiments. A within-subject design was employed for all five experiments and the experimental setup was designed to restrict any changes in digit forces due to biomechanical factors. Thus, any changes in the dependent variables could be attributed to the neural factors alone. Results from the first three experiments indicate that loss of cutaneous feedback due to digital anesthesia results in up to 25% decrease in MVF, while the stimulation of cutaneous receptors by TENS or by changing the surface texture results in up to 20% increase in MVF. Results from the last two experiments indicate that providing a real-time visual feedback of digit forces increases the MVF by up to 25%, while a fifteen minute exposure to high intensity ambient light increases the MVF by up to 20%. In addition, MDI also depends on the type of sensory feedback presented to the subjects. These results suggest that both, the magnitude as well as the distribution of neural commands to the hand and forearm muscles changes with different sensory feedback conditions. Potential neuromuscular mechanisms responsible for these changes in MVF and FDI with different types of sensory feedbacks have been discussed.

SENSORY FEEDBACK MODULATES MAXIMUM VOLUNTARY FORCE IN MULTI-FINGER PRESSING

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Chapter 1: Introduction

Problem statement

The human hand is one of the most complex effectors in the body and has played a major role in the evolutionary success of the primates [1]. Conducting individual digit movements as well as combined movements of all the digits together is required to accomplish everyday manipulation tasks. Maximum voluntary force (MVF) production by the digits is an essential part of performing day-to-day activities, and its importance has been well documented in the literature [2-6]. MVF of the digits has widely been used as a clinical measure of functional strength of the body [7]. Further, MVF is frequently needed to perform manipulation tasks while using hand tools in industrial settings, and the design of many hand tools is optimized to produce highest MVF possible [8]. Studies have shown that MVF is higher in adults as compared to children, increases with strength training, decreases with fatigue and aging, and also depends on the emotional state of the participants [9-13]. MVF is known to be lower in patients with sensory deficit disorders as compared to healthy adults [4]. It has been shown that a decrease in the ability to produce MVF is related to a reduction in the quality of life [14]. Further, it is well established that MVF depends on both, the anatomy of the body as well as the motor commands from the central nervous system (CNS) [1, 15-19].

A majority of studies measuring MVF in the human hand have primarily used gripping and pinching tasks, because a lot of everyday manipulation tasks involve similar actions by the hand [20-23]. More recently, multi-digit pressing has emerged as a simpler paradigm to study the motor behavior of the hand [11, 13, 15, 24]. According to mechanics, the maximum force produced by the digits is limited by the maximum normal force produced by the thumb. Further, gripping a free object produces an additional mechanical constraint of balancing the torques, which affects the force production capacity of the fingers. In contrast, pressing task is free from such mechanical constraints and offers an easier paradigm to study motor behavior of the hand.

Force production by the digits during multi-digit pressing is known to exhibit some well documented multi-digit interactions. The first phenomenon, called finger independence (FI) or finger enslaving, refers to the amount of forces generated by other digits involuntarily, when a specific digit is given a voluntary command by the CNS to produce force [25-27]. It has been suggested that FI could be the result of a combination of anatomical as well as central factors. Firstly, peripheral mechanical coupling between the tendons of the finger flexors in the forearm could produce FI [28]. However, it is not yet known if peripheral mechanical coupling plays any role during isometric force production [28]. Secondly, motor units in the compartments of extrinsic hand muscles could act on all the four fingers. Lastly, FI could be the result of motor commands from the CNS leading to co-activation of muscle compartments that flex individual fingers. It has been suggested that FI is largely a result of the central commands, with a little contribution from the peripheral factors [26].

The second phenomenon, called force deficit (FD) refers to the inability of a finger to produce the same force during multi-digit maximum force production, as compared to the maximum force produced when a finger is pressing individually [26]. It has been suggested that FD is the result of a ceiling effect in the common neural drive to the motoneuron pools innervating the muscles involved during maximum finger force production. As the number of fingers producing the force increases, the neural drive is shared amongst those fingers, eventually resulting in lower forces [12, 26].

In the experimental settings where the biomechanical factors are not manipulated, changes in FI and FD have been attributed to the motor commands emanating from the CNS [9, 10, 12, 26, 29]. FI and FD are known to change with aging, strength training as well as fatigue [10, 11, 30] and it has been suggested that the neural adaptations as the result of aging are similar to those observed during fatigue in healthy, young adults. Based on these arguments, an *adaptation hypothesis* has been proposed in the literature, which suggests that a decrease in MVF due to aging or fatigue results in an increase in FI as well as FD [12]. Consistent with this hypothesis, an increase in MVF should correspondingly result in lower values of FI and FD.

Sensory feedback plays an important role in successful completion of everyday dexterous tasks. Specifically, cutaneous, proprioceptive and visual feedback are the primary modalities by which the central nervous system gathers feedback about the environment and makes changes to the motor commands accordingly [20, 29, 31, 32]. MVF, FD and FI are known to change with the changes in motor commands, although it is not yet known how the sensory feedback specifically affects these variables. Typically, strength training has been used as an intervention to increase the MVF of the subjects. However, more recent studies have shown that it might be possible to increase the MVF production capacity of individuals by enhancing the sensory feedback either by changing the properties of the hand or those of the object being manipulated [3, 33, 34].

The purpose of this dissertation is to investigate the effect of changes in tactile and visual feedback on maximum voluntary force (MVF), finger independence (FI) and finger force deficit (FD) during a multi-digit pressing task.

Specific Aim 1: To determine the effect of digital anesthesia on MVF, FD and FI during multi-digit pressing.

Cutaneous afferent feedback provides critical information regarding the current state of the system and enables the CNS to modify the motor plan accordingly [18, 31, 33, 35]. Previous studies have investigated the role of cutaneous feedback on the motor behavior of the hand by administering digital anesthesia during sub-maximal force production tasks [18, 33, 36-39]. These studies have shown that the peripheral afferents have a net facilitatory effect on motoneurons and the magnitude of motor commands from the CNS could depend on the cutaneous feedback available from the digits [40, 41]. Specific aim 1 therefore investigates the effect of digital anesthesia on MVF, FD and FI.

Hypothesis 1: *Maximum voluntary force (MVF) will be significantly lower with the administration of digital anesthesia as compared to the normal condition.*

A recent study used ulnar nerve block to deaffernate the intrinsic muscles as well as the cutaneous receptors of the hand and reported that during attempted maximal voluntary efforts the mean discharge rate of single motor axons was significantly lower than those of normally-innervated motor units [42] . Another study using ring block anesthesia also reported a decrease in the maximum generated forces in a pinch grip task [33]. Based on these studies, it is expected that the loss of cutaneous feedback with the administration of anesthesia will reduce the magnitude of motor commands from the CNS and result in a significant decrease of MVF.

Hypothesis 2: Force deficit (FD) will significantly greater with the administration of digital anesthesia as compared to the normal condition.

FD is primarily thought to have origins at the central level although the exact mechanism of FD is not yet known [12, 26]. Studies on strength training, aging and fatigue have shown significant changes in FD [10, 43]. It has been suggested that changes in FD are the result of changes in the magnitude of motor commands responsible for maximal force production by the digits. Since loss of cutaneous feedback is expected to reduce the magnitude of neural drive emanating from the CNS. It is expected that this reduction would manifest as the change in FD. Based on the adaptation hypothesis [12], a decrease in MVF should result in an increase in FD.

<u>Hypothesis 3</u>: *Finger independence (FI) will be significantly greater with the administration of digital anesthesia as compared to the normal condition.*

Similar to FD, FI is known to depend on both biomechanical and central factors. FI can potentially be due to peripheral mechanical coupling, multi-digit motor units in the extrinsic flexor and extensor muscles or diverging central commands from the central level [15, 25, 26]. While it is not clear how the loss of cutaneous feedback will affect the distribution of motor commands to the finger flexors, based on the adaptation hypothesis [12], FI could be expected to increase with the administration of digital anesthesia.

Specific Aim 2: To determine the effect of transcutaneous electrical nerve stimulation (TENS) on MVF, FD and FI during multi-digit pressing.

Although TENS is widely used in clinical settings to mitigate pain, recent studies on the application of TENS to patients with diabetic neuropathy and Parkinson's disease have shown significant increase in cutaneous sensation [44-48]. It has been suggested that TENS could stimulate one of the four mechanoreceptors, thus increasing the afferent inputs to the sensorimotor cortex [49]. Specific aim 2 therefore investigates the effect of TENS on MVF, FD and FI.

Hypothesis 1: Maximum voluntary force (MVF) would be significantly greater with the administration of TENS as compared to the normal condition.

While the exact neurophysiological mechanism of TENS is not yet known, it has been well established that the mechanism either involves spinal reflexes or the sensorimotor cortex [44, 48-50]. Cutaneous feedback is known to facilitate motor output [36, 51], therefore an increase in cutaneous feedback by administration of TENS could be expected to result in significantly greater MVF.

Hypothesis 2: Force deficit (FD) would be significantly lower with the administration of TENS as compared to the normal condition.

Although the motor output and hence the MVF is expected to increase with the administration of TENS, it is not clear if that increase in MVF would be proportional for all the four digits while pressing individually. Given the complex redundancy in the anatomy of the muscles involved in producing the forces by the digits [23] , this scenario is highly unlikely and changes in FD are expected with the application of TENS. Further, based on the adaptation hypothesis [12], an increase in MVF could be expected to produce a corresponding decrease in FD.

Hypothesis 3: Finger independence (FI) would be significantly lower with the administration of TENS as compared to the normal condition.

Any changes in FI would reveal the changes in the distribution of motor commands to the finger flexors [25] with the application of TENS as compared to the normal condition. Since TENS is expected to affect the motor commands from the CNS, changes in FI with the administration of TENS could be expected. Based on the adaptation hypothesis [12], FI would be expected to decrease with an increase in MVF after TENS administration.

Specific Aim 3: To determine the effect of surface texture on MVF, FD and FI during multi-digit pressing.

There are four classes of low-threshold mechanoreceptors in human glabrous skin innervated by four classes of peripheral afferent nerve fibers [35]. The neurons in the primary motor cortex have receptive fields in the periphery that receive inputs from the primary somatosensory cortex [52, 53]. Changes in cutaneous feedback are thought to be associated with the inputs to the primary somatosensory cortex [32]. It has been suggested that different surface conditions might stimulate different mechanoreceptors, thus altering the afferent feedback to the CNS [54, 55]. Specific aim 3 therefore investigates the effect of surface texture on MVF, FD and FI.

*Hypothesis 1**:** Maximum voluntary force (MVF) will be significantly greater in the low friction, smooth surface condition as compared to the high friction, rough surface condition.*

A recent study on the effect of surface friction on MVF in a pinching task has shown significant differences in the MVF production [3]. Different surface textures could differentially activate one of the four cutaneous mechanoreceptors, thus resulting in different afferent feedbacks which might result in the changes in motor commands from the central level [31]. It is expected that smooth surface texture with low friction will have the particle size small enough to stimulate the mechanoreceptors on the glabrous skin surface of the digits, and result in greater MVF.

Hypothesis 2: Force deficit (FD) will be significantly lower in the low friction, smooth surface condition as compared to the high friction, rough surface condition.

Studies on aging, strength training and fatigue have shown that changes in FD with these independent variables could be attributed to the changes in motor commands as well as muscle morphology [9, 10, 12]. Since smooth texture is speculated to have a net facilitatory effect on motor commands [36], and result in a greater MVF , it could be expected that based on the adaptation hypothesis [12], smoother pressing surface condition would result in lower values of FD as compared to the rougher surface.

Hypothesis 3*: Finger Independence (FI) will be significantly greater in the low friction, smooth surface condition as compared to the high friction, rough surface condition.*

If the change in surface friction results in any changes in the distribution of motor commands to the finger flexors in the forearm, significant changes in FI could be expected. Based on the adaptation hypothesis [12], an increase in MVF would be complemented by a decrease in FI.

Specific Aim 4 **:** *To determine the effect of real-time visual feedback of pressing forces on MVF, FD and FI during multi-digit pressing.*

Real time visual feedback is known to improve task performance in sub-maximal force production tasks and is widely used for rehabilitation of patients with movement disorders [34, 56, 57]. Although MVF production is primarily thought to be controlled by a feed-forward mechanism, some studies on isokinetic maximal force production have shown that presenting the participants with a real-time visual feedback of their performance can significantly increase their force production capacity, thus suggesting the involvement of a feedback mechanism [58]. Specific aim 4 therefore investigates the role of real time visual feedback on MVF, FD and FI.

Hypothesis 1: *Maximum voluntary force (MVF) would be significantly greater during the visual force feedback condition as compared to the normal condition.*

A recent study has shown changes in activation patterns of the extrinsic muscles of the hand, when subjects were instructed to produce isometric forces and given a real time visual feedback of their performance [56]. This study suggests that the motor commands emanating from the CNS could change with the presence of visual feedback. Further, studies on isokinetic MVF production during knee and elbow flexion have shown a significant increase in MVF production with the presence of visual feedback [58]. Although the exact neural mechanisms underlying these changes in maximal force production are not yet known, these studies suggest that MVF production could be based on a feedback control mechanism as opposed to a feed-forward mechanism. If such is the case, presenting the subjects with a real time-visual feedback of their force production should significantly increase MVF.

Hypothesis 2: *Force deficit (FD) would be significantly lower during the visual force feedback condition as compared to the normal condition.*

FD is partly thought to be the effect of changes in the neural drive when forces are produced by individual digits as compared to all the digits pressing together [26]. If the presence of visual feedback during MVF production changes these neural signals in magnitude, those changes should manifest as significant differences in FD. Since visual feedback is expected to result in greater MVF, based on the adaptation hypothesis [12], FD is expected to decrease correspondingly.

Hypothesis 3: *Finger independence (FI) would be significantly greater during the visual force feedback condition as compared to the normal condition.*

While the exact mechanism of FI is not yet known, it has been suggested that FI partly depends on the motor commands to the finger flexors [25]. If the distribution of motor commands to these flexors changes, it results in the changes in FI. Based on a previous study that has shown significantly different muscular activity during force production in the presence of visual feedback [56], it can be expected that the distribution of neural signals, and hence, the FI will significantly lower in the presence of visual feedback.

Specific Aim 5: To determine the effect of ambient light intensity on MVF, FD and FI during multi-digit pressing.

Ambient light has commonly been associated with the emotional state of individuals, and is known to affect the motor performance in multi-digit, sub maximal force production tasks [59-61]. It is well reported that ambient light affects the emotional state of individuals, which in turn is linked to the changes in motor performance. Because of its emotion altering abilities, ambient light has frequently been used to treat seasonal depression and epilepsy [46, 62-64]. Furthermore, a positive emotional state has been associated with successful motor task performance during sub maximal force production tasks. Based on these studies, specific aim 5 investigates the changes in MVF, FD and FI with different levels of ambient light intensities.

Hypothesis 1: *Maximum voluntary force (MVF) would be significantly lower with the lesser ambient light intensity, as compared to the normal condition.*

Hypothesis 2: *Maximum voluntary force (MVF) would be significantly greater with higher ambient light intensity, as compared to the normal condition.*

Previous studies have shown that presenting a positive emotional stimulus to the participants significantly increases their force production capacity during isokinetic tasks [59-61, 65]. This suggests that high arousal level increases the magnitude of motor commands, resulting in higher forces. Since high light intensity is known to produce positive emotional states in individuals [62], it is hypothesized that participants will produce significantly greater amount of MVF when exposed to high intensity light as compared to the normal light intensity. Conversely, it is expected that the MVF would be significantly lower when participants are exposed to no light, as compared to the normal light condition.

Hypothesis 3: *Force deficit (FD) would be significantly lower with the increase in ambient light intensity.*

Since FD is known to emerge partly from the motor commands emanating from the CNS [26], any changes in motor commands magnitude due to the exposure to different light intensities would produce significant changes in FD. Based on the adaptation hypothesis [12], an increase in MVF resulting from changes in light intensity should be complemented by a decrease in FD.

Hypothesis 4: *Finger independence (FI) would be significantly greater with the increase in ambient light intensity.*

FI is also known to partially depend on the motor commands from the CNS [25], and any changes in the distribution of motor commands to the finger flexors after exposure to different light intensities should significantly change FI. Based on the adaptation hypothesis [12], FI is expected to decrease with an increase in MVF due to increased light intensity.

Dissertation organization

This dissertation is organized into nine chapters. The first two chapters elaborate the problem statement and literature review to justify the current research. This is followed by the five experiments, each corresponding to a specific aim, presented in Chapter 3 to 7. The experimental setup for all the studies is designed so that the biomechanical factors involved during the pressing task remain unaltered. Thus, any changes in the dependent variables could be attributed to the changes in the motor commands emanating from the central nervous system.

Chapter 1 serves as an introduction to the research problems. The significance of the research is demonstrated. Five specific aims are proposed from the perspective of different sensory feedback modalities that would be investigated. Chapter 2 elaborates the biomechanical and neurophysiological research on hand and digits. The phenomena of MVF, FD and FI are explained in details and the biological mechanisms behind tactile and visual feedback are discussed. Chapter 3 reports the effect of digital anesthesia on the dependent variables. Chapter 4 investigates the effect of transcutaneous electrical nerve stimulation (TENS) applied to the digits on the dependent variables. Chapter 5 reports the effect of surface texture of the sensors on the dependent variables. Chapter 6 reports the effect of visual feedback of the real-time pressing forces by the digits on the dependent variables. Chapter7 investigates the effect of ambient light intensity on the dependent variables. Chapter 8 discusses the main conclusions drawn from Chapters 3 to 7, while Chapter 9 contains general discussion and limitations of these studies.

Chapter 2: Review of literature

The human hand

Primates are the only animals in which hands have evolved, and this has played a significant part in their evolutionary success [66]. In our daily lives we explore and manipulate a wide range of objects, and there are numerous examples of our dependence on manual dexterity and of our reliance on sensory perception of these objects. The human hand is an excellent example of an effector capable of producing wide range of forces to conduct day-to-day manipulation tasks like pressing, grasping and rotating objects [21]. The enormous complexity of this system, both at the biomechanical level as well as the neuromuscular level, renders numerous questions about the control strategies being employed by the central nervous system (CNS).

Anatomy of the human hand

The human hand is composed of many different bones, muscles, and ligaments that allow for a large amount of movement and dexterity [67]. There are three major types of bones in the hand - phalanges, metacarpals and carpals. Phalanges are the 14 bones that are found in the fingers of each hand. Each finger has three phalanges (the distal, middle, and proximal) while the thumb only has two. Metacarpal bones are the five bones that compose the middle part of the hand. Carpal bones are the eight bones that create the wrist. The carpal bones are connected to two bones of the arm, the ulnar bone and the radius bone. The movements of the human hand are accomplished by two sets of each of these tissues. They can be subdivided into two groups: the extrinsic and intrinsic muscle groups. The extrinsic muscle groups are the long flexors and extensors. They are called extrinsic because the muscle belly is located on the forearm.

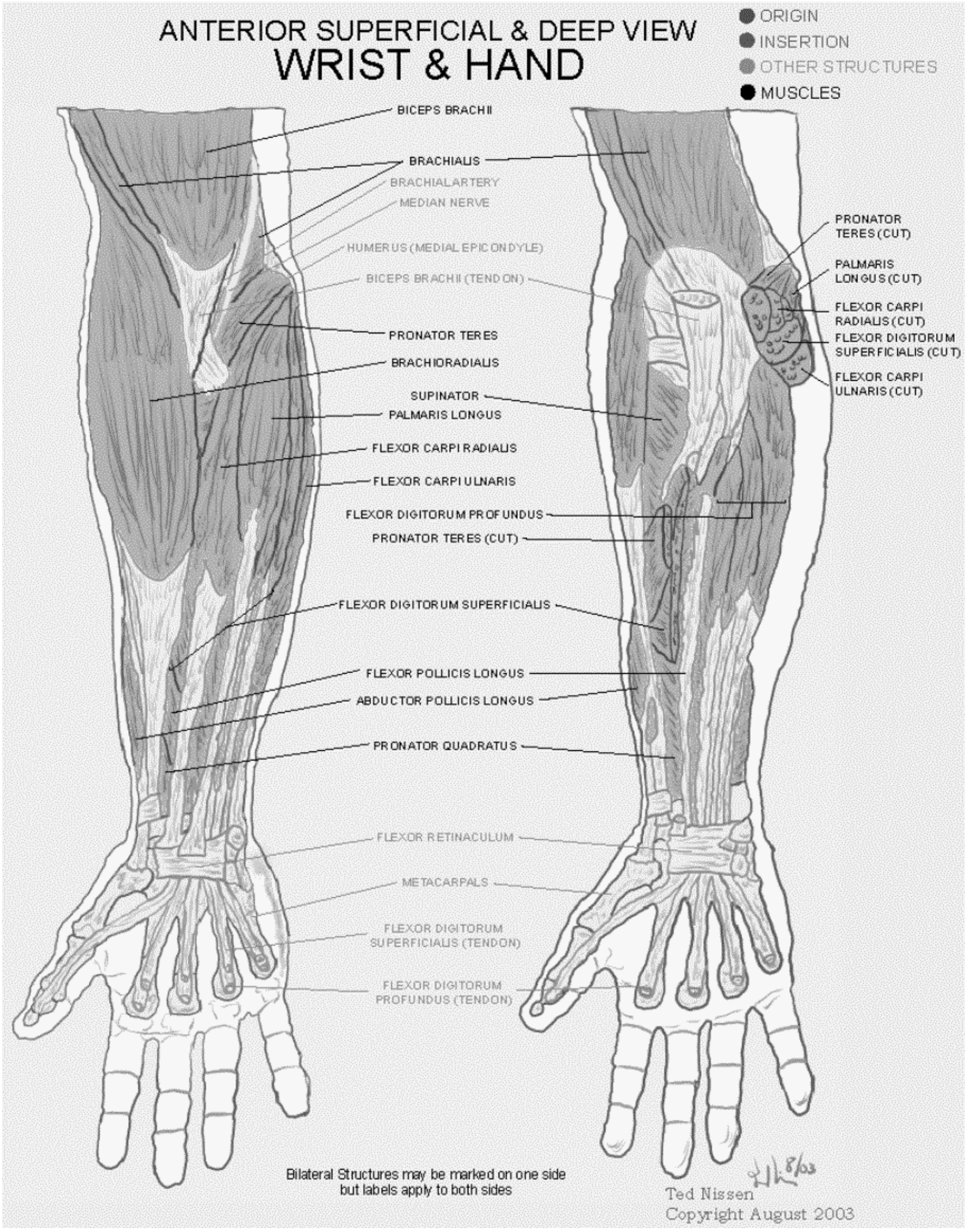


Figure 2.1 Anatomy of the human hand.

The intrinsic muscle groups are the thenar and hypothenar muscles (thenar referring to the thumb, hypothenar to the small finger), the interosseus muscles (between the metacarpal bones, four dorsally and three volarly) and the lumbrical muscles. These muscles arise from the deep flexor (and are special because they have no bony origin) and insert on the dorsal extensor hood mechanism.

In all, 27 bones in the human hand are controlled by 39 muscles. There are many degrees of freedom available for hand motion, yet joint movements are not independent.

Motor cortex and the hand

The human hand has evolved to interact as well as control the environment. Correspondingly, the hand conducts sensory as well as motor functions. It has been suggested that the CNS can regulate the type as well as the amount of the sensory feedback that gains access to the cortical centers involved in the motor tasks [31, 68, 69]. The primary somatosensory cortex (S1) is the major source of somatosensory inputs to motor cortex and is directly connected to the motor cortex. Studies have shown that lesions in the S1 cortex could result in the complete loss of motor functions of the hands, thus confirming the close functional relationship between the two regions in the brain [70]. The functional role of S1 cortex has been studied in relation to several behavioral factors, by modifying the amount of sensory feedback to the CNS. Some of such factors include movement, attention, motivation, intention to move and arousal [70-72].

In nonhuman primates, the primary motor cortex (M1) plays a fundamental role in the execution of skilled manipulatory tasks [73]. It has been shown that lesions of the pyramidal tract remove independent finger movements while the capacity to flex all fingers together stays intact [74]. However, subpopulations of neurons in M1 that project to motoneurons that innervate hand muscles are active while conducting a precision grip but not during power grip although their target muscles may be activated in either grasp [17, 75]. These studies suggest that the neural mechanisms involved during precision grip could be different from those of power grip. However, results from neuroimaging studies in humans have shown that M1 is active during many types of voluntary hand movements [73, 76]. Furthermore the M1, the supplementary motor area (SMA) and the premotor area (PM) are all active while making individual finger movements and when opening and closing the whole hand [77].

The primary motor cortex and the corticospinal pathways are two of the essential brain regions involved in the control of the hand [78]. Based on the properties of the stimulus, like the weight and texture, the neurons in the primary motor cortex of the monkeys are known to show different excitation levels [79]. Both the corticoneuronal pathways and the spinal neural networks are involved in transmitting the signals from the motor cortex to the hand muscles [80].

Transcranial magnetic simulation (TMS) at the hand area of the motor cortex has shown that the tactile feedback from the finger tips is closely related to the central drive from the motor cortex, particularly when the subjects are about to grasp an object [81]. Tasks, in which extrinsic muscles are primarily responsible, like reaching or maximum voluntary force production, however receive the signals from the motor cortex throughout the task production [82].

The control of voluntary hand movements by the motor cortex has been a topic of extensive research. It has been suggested that the CNS might control the synergy using a set of quantitative rules that define certain parameters of activity in the muscles involved, and these synergies exhibit enough flexibility to adjust to different task demands [83, 84]. Studies on tasks involving gripping a manipulendum have shown that when a number of muscles are involved in a task, no pair of muscles shows a highly correlated EMG activity [85]. This suggests that the CNS employs variable combinations of muscle activities to fulfill the task demands. Based on some of the earliest works by Bernstein, this has led to the hypothesis that the CNS controls the synergies at a higher level than at the level of participating muscles [83]. It has been inferred that the motor units in the different muscles involved during the task may receive a common drive from the CNS, suggesting a divergent central control. Divergent corticospinal axons in the spinal cord also point to the fact that some muscle coupling in the hand could be centrally organized in a fixed manner [86, 87]. These findings suggest that the CNS incorporates functional units that may be essential parts of the functional hand movements. The concept of a common central drive has also been substantiated in deafferanted patients, suggesting common motor inputs to multiple muscles [86, 88].

Muscle mechanics and maximum force production

Maximal muscular force depends on the force-velocity relationship and is affected by the length-tension relationship [89]. Specifically, the time available to develop force, interactions of contractile and elastic elements, potentiating of contractile and elastic filaments as well as stretch reflexes affect the force generation capacity of the muscles [89]. Furthermore, maximal force production is influenced by anatomical factors, like the fiber type contribution to whole muscle area, muscle architectural features and tendon properties. In addition, neural factors including motor unit recruitment, firing frequency, synchronization and inter-muscular coordination also determine the force generated by the muscles [89].

The force velocity relationship is one of the major characteristic of the muscle that dictates its maximum force generation capacity [90, 91]. As the single muscle fiber shortens, there is a decrease in its velocity because the contractile force decreases. During concentric muscle contraction, the relationship between the force and the velocity of the single muscle fiber is inversely proportional to each other. Thus, in order to have the maximum force output from the muscle fiber, the velocity of the fibers should be close to zero [92]. However, it is to be noted that the force velocity relationship of the muscle also depends on the design of the muscle itself and the actual shape of the curve between the changes from single fiber to whole muscle.

The second mechanical factor that affects the force generation capacity of the skeletal muscles is the length of the sarcomeres [6]. According to the cross bridge theory, muscle force production is highest when the sarcomere is at an optimum length and the actins completely overlap with the myosin fibers [93, 94]. At the whole-muscle level, the maximum force generation capacity increases with the number of muscle fibers arranged in parallel to each other [94].

Finally, the pennation angle, referring to the angle between the muscle fibers and the direction of the force production also affects the maximum force generation capacity of the muscle [93, 94]. The entire force produced by the muscle fibers is transmitted when the pennation angle is zero, and decreases by a factor of cosine of the angle between the muscle fiber and the direction of force production. Muscles with low ratios of fiber length to muscle length tend to have fibers with greater pennation angle as compared to muscles with high ratios [93, 94].

Multi-digit pressing as a paradigm to study motor behavior of the hand

Numerous studies have been conducted to study the force production capacity of the fingers during grasping and pinching tasks [22, 33, 95-97]. However, more recently, pressing tasks have emerged as a simpler paradigm to understand the motor behavior of the hand [9, 10, 24]. According to basic mechanics, during a static pinch or grip, the force produced by the thumb is equal in magnitude to the total force produced by the opposing fingers. Hence, the maximal values of the total force are limited by the force of the thumb and may not represent the maximal force potential of the fingers. Also, in a gripping task, in order to prevent handle rotation, the individual fingers should produce forces of such magnitudes that the moment of force with respect to the pad of the thumb equals zero. Hence, the force production pattern in gripping tasks may be defined by additional mechanical constraints [26].

Pressing task, on the other hand provide a simpler paradigm as the maximal forces generated by the fingers are free of the abovementioned constraints. Further, it is safe to assume that while pressing, the anatomical and biomechanical constraints do not change, and any change in behavior could be attributed to the central factors. Recent studies on multi-digit pressing have revealed some well documented behaviors of the digits. Firstly, it is well established that the MVF production capacity of the four fingers is significantly different from each other. The index finger is the strongest, followed by the middle, ring and little fingers respectively [24, 26]. While little is known about how different external factors like sensory feedback, motivation, arousal and intent affect the MVF production by the hand, it can safely be assumed that the control strategies for MVF production are similar to what has previously been documented for the MVF production in other parts of the body.

Force deficit (FD)

Studies on multi-digit isometric pressing tasks have shown that the sum of maximal forces produced by the individual fingers is greater than the sum of forces produced by all the fingers together, in a pressing task. This has been referred to as finger force deficit in the literature (FD) [26]. A previous study has shown that FD remains constant across children of different ages, although the MVF increases significantly, thus suggesting a fixed distribution of motor commands across different muscles involved in pressing [11]. Similarly, no significant differences in FD have been observed between healthy subjects and adults [12]. However, higher values of FD have been observed when forces are produced at the proximal phalanges as compared to the distal phalanges, which in turn are controlled by intrinsic and extrinsic muscles respectively [12]. Patient's with Down's Syndrome are also known to exhibit lower FD values, suggesting that changes in FD are a result of changes in central mechanisms of motor command production [98]. Previous studies have suggested that FD could change due to several central factors such as an increased innervation ratio, reduced recruitment of motor units involved or reduced maximal discharge rate [12].

Three potential mechanisms for FD have been suggested in the literature [26]. The first hypothesis suggests that FD is caused by interconnections between the fingers as a result of the anatomical structure of the hand and forearm. Since tendons of the fingers are connected to multiple muscles [99], when individual fingers produce an MVF, more muscles can be employed to produce the force. However, when multiple fingers produce an MVF, same group of muscle forces are distributed among different fingers, thus resulting in the reduced maximal force production capacity of each finger.

A different mechanism for explaining FD attributes the phenomena of efferent synergistic inhibitions among fingers [100]. According to this hypothesis, an activation of one finger inhibits activity of its adjacent fingers. However, more recent experiments have shown that adding additional fingers during multi-digit pressing task did not affect FD values, thus rejecting this hypothesis [26].

The third possible explanation for FD is based on the hypothesis of a two-level control system, originally proposed in the classical works of Bernstein [101]. A central neural drive

(CND) arrives at the level of synergies and is distributed to muscles. An additional assumption is that the CND has a certain limit, a ceiling that cannot be exceeded. As the number of effectors involved in the task increases, the neural drive that is available for each individual effector decreases. This hypothesis is consistent with the data observed in multi-digit pressing tasks, where addition of fingers resulted in higher FD values [26].

Finger Independence (FI)

The motor cortex and the corticospinal tract are vital for the control of relatively independent finger movements [74]. The convergence and divergence of motor cortical cells onto the spinal motor- and inter-neurons affords the ability to selectively activate groups of muscles to perform complex finger movements. Despite this highly evolved control system, humans cannot move their fingers completely independently [102], nor can they produce completely independent finger forces [25, 27, 102]. When a person produces isometric force with fingertips of one, two, or three fingers, the other fingers of the hand also produce a certain force, and this phenomenon has been called finger force enslaving in the literature [28]. FI is the involuntary force production by non-intended fingers. The explicitly involved fingers are termed master fingers, and the other force-producing fingers are called slave fingers. Due to FI, no direct correspondence exists between the neural commands to individual fingers and finger forces. To produce a desired finger force, a command sent to an intended finger should be scaled in accordance with the commands sent to other fingers. FI is a quantitative measure of the combined action of several factors. FI can potentially be due to peripheral mechanical coupling, multi-digit motor units in the extrinsic flexor and extensor muscles and diverging central commands [103].

Muscle compartments of the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) may contain motor units that act on all four fingers [104]. At the central level, FI may be a result of a central organization leading to a co-activation of muscles and muscle compartments that serve different digits [105]. The representations of different fingers in the primary motor cortex have been shown to overlap extensively within the motor cortex [105]. However, the contributions of mechanical and neural factors to the interdependence among finger forces are not yet clear. FI could be caused by muscle fibers activated within the deep flexor of one finger, but inserted into the deep flexor of another finger [103].

Sensory Control of Dexterous Manipulation

The human hand has evolved to conduct a wide range of functions, ranging from tasks that require object manipulation to tasks that demand exploration of the environment. During object manipulation, sensory signals from the digits are used by the motor system to perform the task. During exploratory tasks, sensory signals from the digits are primarily used for perception and cognition and enable effective scanning of the surface.

While vision plays a significant part in manipulation, somatosensory feedback is as important to successfully conduct manipulation tasks as well. Studies on patients with large fiber sensory neuropathy, with severely damaged hand function have emphasized the role of somatosensory feedback [4]. Conversely, precise manipulation is possible without vision, proven by the fact that blind people are dexterous [106]. While the exact mechanisms at the level of neural networks of the sensorimotor control of human hands are not yet known, pressing and prehension movements involve most areas known to be involved in the control of other limbs in the body. Specifically, the primary motor cortex, basal ganglia, cerebellum and the sensory and association cortex are primarily involved in day to day dexterous manipulation tasks [97, 107, 108].

Tactile Feedback

One of the important sensory feedback mechanisms for dexterous manipulations is the cutaneous feedback from the digits [21]. Cutaneous afferent feedback provides critical information regarding the current state of the system and enables the central nervous system (CNS) to modify the motor plan accordingly [18, 20, 40]. Different types of cutaneous receptors provide feedback about the shape, texture, pressure, temperature and other physical properties of objects to the CNS during manipulation [21, 31, 32, 109].

Glabrous skin of the digits is highly specialized. There are four classes of low-threshold mechanoreceptors in human glabrous skin innervated by four classes of peripheral afferent nerve fibers [110]. The more superficial Merkel complexes and Meissner corpuscles are innervated by slowly adapting type I afferents (SAI afferents) and so-called fast-adapting type I afferents (FAI afferents), respectively. The deeper Ruffini organs and Pacinian corpuscles are innervated by slowly adapting type II (SAII) afferents and fast-adapting type II (FAII) afferents, respectively. It is noteworthy that skin mechanics also plays a major role in the transduction of tactile stimuli into afferent responses [31].

The fingertips of the human hand are amongst the highest intensity of sensory receptors in the body. Information is transmitted to the CNS from the mechanoreceptors in the fingers and the control strategy for day-to-day tasks largely relies on cutaneous feedback from the fingers [21]. However, how the various sensory modalities are combined in the somatosensory cortex and translated into motor behavior of the hand has been a matter of elaborate research.

Previous studies have administered digital anesthesia as a primary modality to remove cutaneous feedback from the digits and investigated the role of cutaneous feedback on CNS control over hand and finger actions [18, 29, 33, 36]. Studies on sub-maximal force production tasks such as grasping and pinching have shown that effective removal of cutaneous feedback leads to an increase in errors during motor performance [38, 111, 112]. The extent of cutaneous feedback is known to change with the digits involved in the task and also affects the forces being perceived by the digits during weight matching tasks [37, 40, 41, 103]. Further, patients who have lost cutaneous feedback as a result of sensory neuropathy have also been reported to produce inaccurate as well as lower amount of sub-maximal forces [4, 113, 114].

The effect of transcutaneous electrical nerve stimulation (TENS) has widely been studied in patients with hemiplegia, diabetic neuropathy, stroke and other sensory deficit disorders [115, 116]. Primarily, TENS is a form of somatosensory stimulation as well as neuromuscular stimulation. It has been shown that a single session of TENS could increase the cutaneous sensation in the patients and the effects last for up to 45 minutes after a brief, 20 minute session of TENS. While the exact neurophysiological mechanism of this phenomenon is not yet known, it has been suggested that that TENS could enhance the somatosensory input to the CNS [48]. Although the exact neurophysiological mechanism of this phenomenon is not yet known, it has been suggested that that TENS could enhance the somatosensory input by selectively stimulating certain afferent fibers, which in turn could modulate the motor output [44, 48]. Further, different parameters of TENS are known to have a varied effect on the neuromuscular system, and frequency of TENS stimulation has been shown to be one of the most important parameters [45, 117].

A recent study on maximum isometric force production between the thumb and the index finger revealed that the normal force production of the fingers increases with the increase in the friction coefficient between the fingers and the manipulendum [3]. Consistent with results from the aforementioned study, evolutionary biologists have suggested that the fingerprints on the fingers have evolved in order to increase the friction coefficient of the fingers, and higher friction coefficient is thought to be related to the production of higher forces. The neurons in the primary motor cortex have receptive fields in the periphery that receive inputs from the primary somatosensory cortex [118]. Changes in cutaneous feedback are thought to be associated with the inputs to the primary somatosensory cortex [32, 118]. Although studies investigating the change in friction on sub-maximal force production tasks have pointed towards the changes in central mechanisms affecting the motor output, the role of surface friction on MVF production is not known.

Visual Feedback

Under normal circumstances, vision plays a significant role in hand movements, and this is starting to be addressed at a number of levels including hand-eye coordination [20]. Studies on the posterior parietal cortex have shed light on the complex interactions between visual sensory input, somatosensory input, and other sensory input in planning and executing hand movements [119].

It has been suggested that there are two distinct visual systems in the primal visual cortex mediating dexterous manipulations. The ascending visual pathways of the cerebral cortex in the primates project to a complex network of interconnected areas which contain visually sensitive neurons. These neurons are known to be sensitive to different visual stimuli. Specifically, a ventral stream of projections originates from the primary visual cortex (V1) [120] and project to the inferotemporal cortex and a dorsal stream projects from V1 to the posterior parietal cortex. Previous studies suggest that the ventral stream is responsible for the visual identification of the objects and the dorsal stream is responsible for localizing objects in visual space. Both the dorsal and the ventral streams process information about object characteristics like the shape, size and the orientation as well as the location of the object. However, only the transformations carried out in the dorsal stream are known to mediate the control of goal directed action.

Many studies have investigated the role of visual feedback in sub-maximal isometric force production tasks [56, 121, 122]. Studies have shown that presenting the subjects with a real time visual feedback of the motor task performance during multi-digit isometric force production tasks produces lower force variability [122, 123]. In a similar task setting, visual feedback has also shown to improve the motor performance in patients suffering with stroke and DCD [124]. A recent study reported a change in muscular activity with the presence of visual feedback during a dexterous manipulation task, thus suggesting the presence of visual feedback could change the motor commands flowing from the central nervous system (CNS) to the muscles [56]. Despite a number of studies investigating the role of visual feedback in sub maximal finger force production tasks, it is not known how the real time visual feedback affects the MVF production by the fingers and the related inter-digital phenomena like FI and FD during isometric pressing.

Studies on isokinetic torque production have shown that presenting the subjects with a real time visual feedback and the target force could significantly increase their maximum torque generation capacity [58, 125, 126]. Studies on sedentary subjects measuring isokinetic torque production at the knee joints, as well as the quadriceps and hamstrings have shown a significant increase in the torque production capacity with the presence of online visual feedback [58, 125].

Apart from the visual feedback of the task and the effector, external light conditions are also known to affect the motor performance. It is well documented that ambient light affects the emotional state of individuals, which in turn is linked to the changes in motor performance [62, 127, 128]. Studies have suggested that dimly lit work environments reduce workers' emotional state, while emotional state improves as ambient light increases to a specific point [62, 64]. Because of its emotion altering abilities, ambient light has frequently been used to treat seasonal depression and epilepsy [127-129]. Furthermore, a positive emotional state has been associated with successful motor task performance during sub maximal force production tasks. People in positive emotional states have the ability to focus their attention fully on the task and thus perform the task at hand more successfully [61, 130]. Exposure to emotional state changing stimuli is known to interfere with movement that requires greater attentional resources [61]. Studies have also shown that while performing simple motor tasks, such as pinching, stimuli arousing both positive as well as negative emotions impair performance, however the decline in motor performance is more drastic when the stimulus arouses a negative emotion [131].

When examining the effect of emotional stimuli on force production, varying results have been reported in the literature. Studies have shown that regardless of emotional state, pleasant or unpleasant, there is an increase in the maximum force production. In one such study, emotional state was manipulated by using 20 digitized photos obtained from the International Affective Picture System [60]. These images were selected according to their affective normative rating, matching arousal between pleasant and unpleasant images and differentiating these images from neutral images. Other studies have found that negative emotional stimuli have a greater effect on increasing force production than positive emotional stimuli [59].

Chapter 3: Tactile feedback plays a critical role in maximum finger force production

Abstract

This study investigates the role of cutaneous feedback on maximum voluntary force (MVF), finger force deficit (FD) and finger independence (FI). FD was calculated as the difference between the sum of maximal individual finger forces during single-finger pressing tasks and the maximal force produced by those fingers during an all-finger pressing task. FI was calculated as the average non-task finger forces normalized by the task-finger forces and subtracted from 100 percent. Twenty young healthy right-handed males participated in the study. Cutaneous feedback was removed by administering ring block digital anesthesia on the 2nd, 3rd, 4th, and 5th digits of the right hands. Subjects were asked to press force sensors with maximal effort using individual digits as well as all four digits together, with and without cutaneous feedback. Results from the study showed a 25% decrease in MVF for the individual fingers as well as all the four fingers pressing together after the removal of cutaneous feedback. Additionally, more than 100% increase in FD after the removal of cutaneous feedback was observed in the middle and ring fingers. No changes in FI values were observed between the two conditions. Results of this study suggest that the central nervous system utilizes cutaneous feedback and the feedback mechanism plays a critical role in maximal voluntary force production by the hand digits.

Introduction

The human hand is one of the most versatile organs of the body and is the primary tool by which humans manipulate objects. One of the important sensory feedback mechanisms for dexterous manipulations is the cutaneous feedback from the digits [21]. Cutaneous afferent feedback provides critical information regarding the current state of the system and enables the central nervous system (CNS) to modify the motor plan accordingly [18, 20, 40]. Different types of cutaneous receptors provide feedback about the shape, texture, pressure, temperature and other physical properties of objects to the CNS during manipulation [21, 31, 32, 109].

Previous studies have administered digital anesthesia as a primary modality to remove cutaneous feedback from the digits and investigated the role of cutaneous feedback on CNS control over hand and finger actions [18, 33, 36-38, 51]. Studies on sub-maximal force production tasks such as grasping and pinching have shown that effective removal of cutaneous feedback leads to an increase in errors during motor performance [38, 111, 112]. Cutaneous feedback is known to change with the digits involved in the task and also affects the forces being perceived by the digits during weight matching tasks [37, 40, 41, 103]. Further, patients who have lost the cutaneous feedback as a result of sensory neuropathy have also been reported to produce inaccurate and lower amount of sub-maximal forces [113, 114].

Maximum voluntary force (MVF) production by the digits is an essential part of performing day to day activities, and its importance has been well documented in the literature [9, 19, 28, 29]. As opposed to sub-maximal force production tasks such as everyday pressing and grasping where fine motor control with effective cutaneous feedback is vital for successful motor performance, maximal force production may utilize different control mechanisms. However, there is little information available on the role of cutaneous feedback during MVF production, and it is unclear if and how the cutaneous feedback plays a role in the maximal force producing capacity of the hands. A previous study on the effect of anesthesia during a pinching task showed that cutaneous feedback might play a role in MVF in pinching [33].

Further, several behavioral aspects of pressing have been well documented in the literature [11, 26]. It has been shown that when a single digit produces a voluntary force, the other fingers produce an unintended force. This effect has been called finger enslaving (FE) or finger independence (FI) in the literature [25, 26]. It has also been shown that the sum of maximal forces produced by the individual fingers is greater than the sum of forces produced by all the fingers together, in a pressing task. This has been referred to as finger force deficit in the literature (FD) . Both FI and FD are thought to depend on the central as well as biomechanical factors [10, 26, 132]. Studies have shown differences in FI and FD with aging, gender, strength training and the phalanges of the fingers being used while pressing [9-11, 133]. However, little is known about the role of cutaneous feedback on MVF, FD or FI.

The purpose of this study was to investigate the role of cutaneous feedback in maximum force production by single hand digits as well as multiple digits of the hand during pressing tasks. It was hypothesized that the MVF values would decrease, FI values would decrease while the FD values would increase during MVF production by fingers after the removal of cutaneous feedback.

Methods

Subjects

Twenty healthy volunteers (sex: males, age: 23.95±1.00 years, body mass: 68.00±5.21 kg, height: 174.67±5.59 cm), with no history of neurological disorders, participated in the experiments. All the participants were right handed according to the criteria of Edinburgh handedness test. The hand length measured from the middle finger tip to the lunate of the wrist was 17.18±1.02 cm, and the hand width measured across the metacarpophalangel (MCP) joints of the index and little fingers was 9.48±0.60 cm. All the participants gave informed consent based on the procedures approved by the Internal Review Board.

Experimental Setup

The experimental setup included four two-directional (tension and compression) force sensors for four fingers (2nd–5th fingers) with amplifiers (Models 208 M182 and 484B, Piezotronics, Inc.). The sensors were mounted on a customized aluminum frame (14.0 x 9.0 x 1.0 cm) and had parallel slits aligned vertically (14.0 cm). These slits enabled adjustments to the sensors according to the hand and finger sizes of the subjects. A C- shaped aluminum thimble was attached at the bottom of each sensor. Thimbles were placed at a fixed distance of 3cm in the mediolateral direction, such that the distal phalange of each finger could comfortably rest on an individual sensor. Signals from the sensors were conditioned, amplified, and digitized at 1,000 Hz with a 16-bit A/D board (PCI 6034E, National Instruments Corp.) and a custom software program made in LabVIEW (LabVIEW 7.1, National Instruments Corp.). A desktop computer (Dimension 4700, Dell Inc.) with a 19 in. monitor was used for data acquisition. Offline data processing was done using customized programs written in MatLab (MATLAB 7, MathWorks, Inc.).

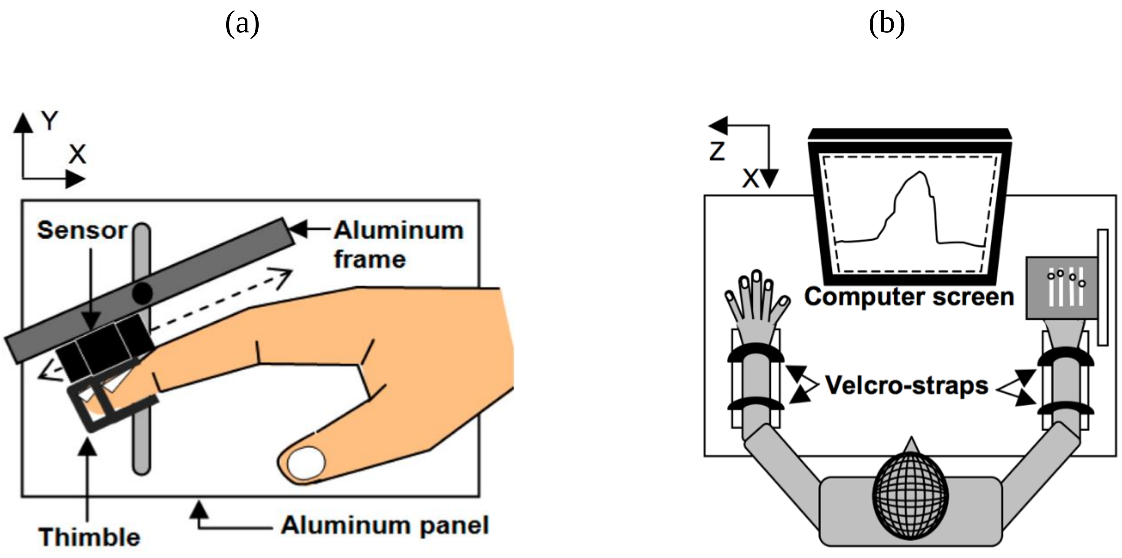


Figure 3.1 (a) Subjects were instructed to insert the distal phalanges of the fingers in the thimbles attached to a customized aluminum frame. (b) A real-time visual feedback of the force production was presented on a computer monitor to the subjects.

Procedure

Subjects were asked to rest the distal phalanges of each of the four fingers of the right hand in the C-shaped thimbles, such that all joints were slightly flexed and formed a dome shape with the hand (Figure 3.1a). The MCP joints were flexed at about 25°. The flexor surface of the palm and the fingers was not restrained physically in order to prevent any tactile feedback from the cutaneous receptors in the palm. Subjects were instructed to sit on a chair facing a computer screen, with the shoulder abducted 35° in the frontal plane and elbow flexed 45° in the sagittal plane. The forearm rested on the customized wrist-forearm brace (comprised of a piece of foam that was attached to a semi-circular plastic cylinder) fixed to a wooden panel (29.8×8.8×3.6) cm. Two Velcro straps, one near the wrist and the other near the elbow, were used to avoid any wrist joint or forearm movements. In order to remove the gravitational effects of the fingers, the force signals for the initial 0.5 s were averaged for each finger and subtracted from the later signals.

Thus, only the force signals due to active force production were shown on the computer monitor in real-time to subjects (Figure 3.1b).

Five different finger combinations (four single-finger tasks and one four-finger task) for the MVF task were presented to the subjects. Subjects were shown the force being produced by task finger or fingers on the screen. One trial was performed for each condition. The five conditions were presented to the subjects in a randomized order, with an interval of 3 minutes between consecutive pressing conditions. Once the subjects had comfortably positioned the fingers on their sensors, the investigators started the data collection program and it generated a "get ready" sound. This was followed by a "ding" sound after 2 seconds. Subjects were instructed to "press as hard as possible with the task finger and relax the fingers once they feel they cannot press any harder". After 7 seconds, another audio cue in the form of a "ding" sound was presented to indicate the end of the trial. Throughout the trial, subjects were given a real time visual feedback of their force performance in the form of a horizontal bar on the computer screen, which moved in the downward direction as the subjects pressed on the sensors with the task finger. The vertical axis on the visual feedback being presented was labeled with the task finger force in Newton, with an increment of 10 Newton force. No subject reported fatigue.

This process was repeated for two different experimental conditions. In one condition, subjects were asked to press the sensors and follow the experimental protocols in the normal condition. In another condition, five minutes after a topical anesthesia (Dermacain Cream 5%, Hana Pharm Co., LTD, Seoul, Korea) was applied to the digits, local anesthesia (Lidocaine HCI 1%, DaiHan Pharm. Co., Ltd., Seoul, Korea) was injected at four sites around the middle phalanges of all four fingers (35 cc. for index, middle and ring fingers; 25cc. for little finger). This was followed by a stroking massage in the direction of distal phalanges. Von Frey tactile hair stimulation was used to assess the threshold of tactile sensation in the normal and anesthesia condition [39]. Cutaneous anesthesia was defined as the inability of the subjects to detect the application of Von Frey filament exerting a force of 4N to the distal pad of the digits. In the normal condition, subjects were able to detect the filament size of (2,44), while in the anesthesia condition, they were unable to detect the filament with the maximum diameter (size 6,65).

Data Processing

Maximum voluntary force (MVF) was measured as the peak forces produced by task finger or fingers during single-finger tasks and a four-finger task. The force deficit (FD) for each finger, FD_i, was calculated as the difference of the maximum force produced by an individual finger in a single finger task, $F_{i,i}$, and the force produced by the same finger in the four finger task, $F_{i,\mathrm{IMRL}}$ (Eq. 1).

$$\mathrm{FD}_i = F_{i,i} - F_{i,\mathrm{IMRL}} \tag{1}$$

The overall FD was calculated by taking the average FD values across all single-finger tasks (FD_i). Further, FD values in the normal condition were expressed as a percentage of those in the anesthesia condition for the purpose of comparison.

The average value of FI across all the four fingers was calculated as shown below (Eq. 2).

$$\mathrm{FI} = 100 - \frac{\sum_{j-1}^{n}[100\% * \sum_{i=1}^{n}(F^{ij}/F^{i}_{max})/(n-1)]}{n} \tag{2}$$

Where$i \neq j$, n =4,$F^{i}_{\max}$ is the maximal force produced by the finger i, and $F^{ij}$is the involuntary force produced by the non-task finger i during the j finger MVF task.

Statistics

One-way repeated-measures ANOVA’s were conducted to compare the MVF, FD and FI values between the two conditions, with and without anesthesia. The level of statistical significance was set at $p = .05$.

Results

Maximum Voluntary Force (MVF)

The MVF values during single-finger tasks decreased significantly after the administration of local anesthesia for all the finger combinations (Figure 3.2a). Specifically, the average values of MVF decreased from 42.15±1.84N to 34±1.90N in the index finger task, from 36.05±1.63N to 30.22±1.42N in the middle finger task, from 26.01±1.54N to 21.10±1.34N in the ring finger task, from 21.81±1.19N to 17.51±0.95N in the little finger task and 113.84±5.51N to 113.84±4.91N in all the four fingers pressing together (Figure 3.2b). Decrease in MVF values after the administration of anesthesia was statistically significant for the individual fingers (Index: $F_{1,19}$= 25.63, p<.001; Middle: $F_{1,19}$ = 19.14, p<.001, Ring: $F_{1,19}$ =18.15, p<.001, Little: $F_{1,19}$ = 12.18, p<.05) as well as the four-finger task ($F_{1,19}$ = 46.09, p<.001).

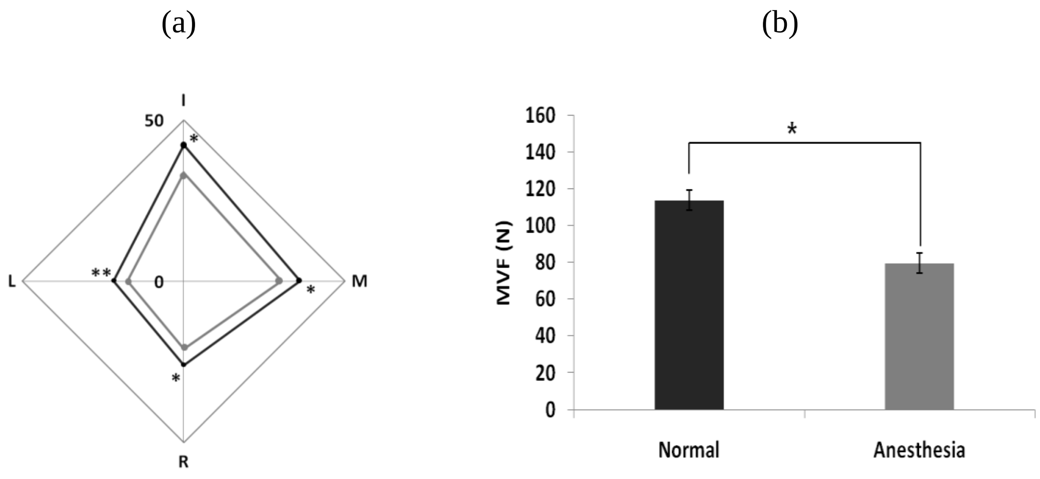
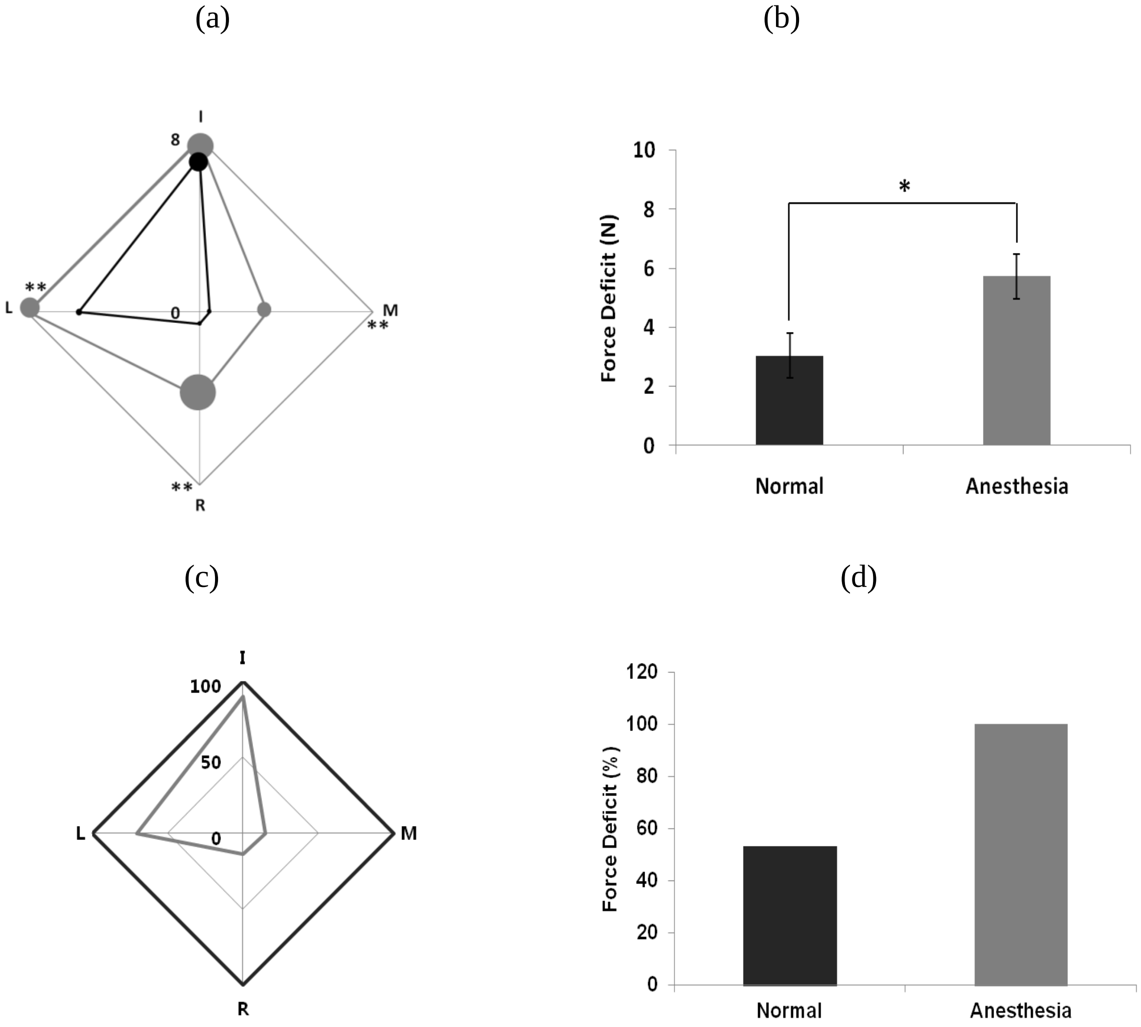


Figure 3.2 (a) MVF in N, produced by the individual fingers of the subjects in the normal condition (outer black lines) and after the administration of anesthesia of the distal phalanges of the fingers (inner grey lines). Radii of the data-point circles represent the standard errors of the mean. I, M, R, and L as shown in each axis represent the index, middle, ring and little finger tasks, respectively. The data are showed in the scale between 0 N and 50 N. (b) MVF values for four-finger tasks with and without anesthesia administration. Means and standard errors are shown across the subjects (*=p<.001; **=p<.05).

Force Deficit (FD)

The force deficit (FD) generally increased after the administration of anesthesia (Figure 3.3a). The increases in FD values were significant for middle, ring and little fingers (Middle: $F_{1,19}$= 15.25, p<.05; Ring: $F_{1,19}$ =6.85, p<.05, Little: $F_{1,19}$ = 3.92, p<.05). FD value changed from 0.47±0.30N to 3.13±1.28N for the middle finger, from 0.55±0.48N to 3.96±1.20N for the ring finger and 5.58±0.88N to 7.92±1.02N for the little finger. FD value for the index finger in the normal condition was 7.13±1.72N as compared to 7.91±1.57N in the anesthesia condition, although this change was not statistically significant. The average FD values for all the four fingers together also increased significantly from 4.25N±0.97N to 6±1.32N after the administration of local anesthesia (Figure 3.3b). The results were supported by ANOVA ($F_{1,19}$ =

46.09, p<.001). On average, FD values in the normal condition were 50% of those in the anesthesia condition (Figures 3.3c and 3.3d).


(a)

(b)

(c)

(d)

Figure 3.3 (a) FD in N, calculated from single-finger tasks in the normal condition (inner black lines), and after the administration of anesthesia (outer grey lines). Radii of the data-point circles represent the standard errors of the mean. I, M, R, and L as shown in each axis represent the index, middle, ring and little finger tasks, respectively. The data are showed in the scale between 0 N and 8 N. (b) Average FD over all four fingers. (c) FD in the normal condition expressed as a percentage of FD in the anesthesia condition. (d) Average FD over all four fingers, with FD in the normal condition expressed as a percentage of FD in the anesthesia condition. Means and standard errors are shown across the subjects (*=p<.001; **=p<.05).

Finger Independence (FI)

No significant changes in the FI values were observed. The FI value in the normal condition was 77.05±5.23% while that after the administration of digital anesthesia was 80.91±6.79% ($F_{1,19} = 3.07$, $p>.05$).

Discussion

Decrease in the MVF values after the removal of cutaneous feedback is similar to the findings from a previous study on a deafferanted hand [42]. Previous studies have shown that the peripheral afferents have a net facilitatory effect on the motoneurons [36, 41, 134]. One of such studies used ulnar nerve block to deaffernate the intrinsic muscles as well as the cutaneous receptors of the hand, and it was reported that during attempted maximal voluntary efforts the mean discharge rate of single motor axons were significantly lower than those of normally-innervated motor units [42]. Another study using ring block anesthesia also reported a decrease in the maximum generated forces in a pinch grip task, although the study did not discuss this finding in details [33]. It is known that the maximum flexion forces generated at the distal phalanges of the digits are primarily produced by the extrinsic hand muscles, the flexor digitorumprofundus and flexor digitorumsuperficialis, which are multi tendoned, with each muscle having an insertion into several digits [135]. Since the ring block anesthesia does not affect either the intrinsic or the extrinsic muscles of the hand, changes in MVF and FD after the removal of cutaneous feedback could be attributed to the changes in the magnitude of motor commands from the CNS.

Previous studies employing a similar task in fatigued fingers as well as in elderly populations have also reported a reduction in MVF comparable to those observed in this study

[30, 43]. It has been suggested that the reduction in MVF during fatigue or aging could result from the drop in maximal discharge rate of the motor neurons, which in turn has been suggested to result either from the elongated post spike motorneuron after hyperpolarization or from changes in the central commands to accommodate the slowed contractile properties of the muscles [12]. Unlike fatigue or aging, it is unlikely that the contractile properties of the muscles change after the application of ring block anesthesia. However, it is to be noted that the administration of anesthesia not only affects the cutaneous receptors, but also tendon organs, thus removing feedback related to muscle contraction [136] .

If the drop in the MVF observed in this study occurs because of a decrease in the discharge rate of motor neurons, this would suggest a dependency of the maximum motor output on the existing cutaneous feedback available to the CNS. Previous studies have shown that the presence of visual feedback could improve the sub maximum voluntary force production performance during isometric tasks, although the role of visual feedback during MVF production during isometric pressing is a matter of further research [113]. Another mechanism that may have contributed to the changes in the MVF found in our study is a change in the mechanical properties of the fingertips with the injection of anesthesia, thus affecting the friction coefficient between the finger coefficients and the sensors. A recent study on maximum pinch force production has shown significant effects of surface friction on force magnitude [3]. However, it is unlikely that a 25% decrease in the MVF could occur by slight changes in the frictional properties of the glabrous skin alone.

The neurons in the primary motor cortex have receptive fields in the periphery that receive inputs from the primary somatosensory cortex [20]. Since the cutaneous feedback in the present study was removed before the MVF production task was performed, it is possible that the absence of cutaneous feedback might have affected the primary somatosensory cortex, thus resulting in a decreased motor output. If this hypothesis is accepted, MVF should increase when the cutaneous feedback is increased, by either changing the surface condition of the force sensors or by stimulating the digits with a mild electric current. However, this remains a matter of further investigation. The primary motor cortex also receives inputs from the posterior parietal areas, which integrate multiple sensory modalities for motor planning. While cutaneous feedback is thought to be the primary source of sensory inputs, visual feedback has also been known to provide afferent inputs in the absence of tactile feedback [113, 137].

FD values observed in the study showed an increase with the loss of cutaneous feedback, in comparison to MVF which decreased with the administration of digital anesthesia. A previous study has shown that FD remains constant across children of different ages, although the MVF increases significantly, thus suggesting a fixed distribution of motor commands across different muscles involved in pressing [11]. Similarly, no significant differences in FD have been observed between healthy subjects and adults [12]. However, higher values of FD have been observed when forces are produced at the proximal phalanges as compared to the distal phalanges, which in turn are controlled by intrinsic and extrinsic muscles respectively [12]. Patient’s with Down’s Syndrome are also known to exhibit lower FD values, suggesting that changes in FD are a result of changes in central mechanisms of motor command production [11]. The changes in FD with the administration of anesthesia observed in this study could be a result of an increased amount of motor commands flowing to the intrinsic hand muscles. Previous studies have suggested that FD could change due to several central factors such as an increased innervation ratio, reduced recruitment of motor units involved or reduced maximal discharge rate [12]. It has been suggested that the motor commands to the instructed digits result in a “spillover” to the antagonist muscles neighboring digits, thus resulting in an increase in FD [12]. No matter what the mechanism for the reduction in MVF after the removal of cutaneous feedback is, changes in FD suggest that not only the magnitude of motor commands change, but their distribution to the muscles might change as well after the cutaneous feedback is removed from the digits.

Results from this study show that the values of FI remain unaltered after the administration of digital anesthesia. This suggests that the distribution of motor commands among different digits of the hand remains unaltered, irrespective of the sensory feedback and results in a proportional decrease of enslaved finger forces. Since it is reasonable to assume that the biomechanical factors in this study were not changed with anesthesia, the unchanged FI values can be assigned to the unchanged central factors associated with the independent actions of fingers.

Increase in FD values with the removal of cutaneous feedback suggest that the magnitude of MVF reduction, and hence the amount of motor discharge, changes differentially for different fingers. Reduction in MVF values as well as FD, along with no changes in FI suggest that cutaneous feedback could play a major role in regulating the amount of motor command from the brain, but not the distribution of those commands to different fingers.

In conclusion, this study reports a decrease in the MVF and increase in the FD with the removal of cutaneous feedback from the digits through anesthesia. While the neurophysiological mechanism for this finding needs further investigation, it is proposed that similar to sub-maximal force production tasks, cutaneous input is an important requirement to achieve maximum force production by the hand digits.

Chapter 4: Fifteen minute treatment with low frequency, high intensity transcutaneous electrical nerve simulation (TENS) increases maximum finger force production

Abstract

The purpose of this study was to investigate the effect of transcutaneous electrical nerve stimulation (TENS) treatment on maximum voluntary force (MVF) production. Ten healthy, young subjects (5 males and 5 females) participated in the study. MVF was recorded after a fifteen minute session of TENS stimulation under two conditions: low frequency (4Hz) at maximum tolerable level and high frequency (110Hz) at maximum tolerable level. TENS was provided simultaneously via self-adhesive electrodes placed on the finger pads of the index, middle, ring and little fingers. MVF was also recorded in a baseline condition with no TENS treatment. Data were collected in three different sessions on three consecutive days at the same time of the day. Results from the study show that on an average, MVF increases by 25% for the index, middle and little fingers for TENS treatment with 4Hz frequency as compared to the baseline condition. However, the 110Hz condition did not result in a significantly different MVF than the baseline condition during individual finger pressing tasks. In addition, while producing MVF with all the four fingers together, MVF was 30% higher for the 4Hz condition in comparison to the baseline condition, and 15% higher for the 110Hz condition in comparison to the baseline condition respectively. The results suggest that stimulation of afferent fibers on the glabrous skin with TENS could have a net facilitatory effect on the maximum motor output.

Introduction

Cutaneous feedback is one of the primary sensory modalities for successful completion of day-to-day dexterous manipulation tasks [31, 33] and loss of cutaneous feedback from the fingers has been reported to produce lower magnitudes of maximum voluntary force (MVF) production [29, 33]. Lower MVF by the fingers is known to be a predictor of poor general health conditions [14].

Although it is well established that loss of cutaneous feedback results in a decrease in maximal force production [29, 33], if the maximum motor output could be enhanced by increasing the cutaneous feedback from the fingers is not yet known. In recent years, transcutaneous electrical nerve stimulation (TENS) has emerged as an important treatment to enhance the cutaneous sensation in patients with sensory deficits [138, 139]. Although the exact neurophysiological mechanism of this phenomenon is not yet known, it has been suggested that that TENS could enhance the somatosensory input by selectively stimulating certain afferent fibers, which in turn could modulate the motor output [44, 48]. Further, different parameters of TENS are known to have a varied effect on the neuromuscular system, and frequency of TENS stimulation has been shown to be one of the most important parameters [45, 117].

The purpose of this study is to investigate the effect of low frequency (4Hz) TENS as well as high frequency (110Hz) TENS on MVF production during multi-digit pressing. It has been hypothesized that TENS treatment would facilitate the motor output by enhancing the cutaneous feedback during multi-digit pressing, thus resulting in greater MVF.

Methods

Subjects

Ten healthy young volunteers (5 males and 5 females, age: 21.0±2.3 years) participated in the study. These individuals were screened for any history of neurological disorders and were right handed according to the criteria of the Edinburgh handedness test. Participants were also administered a questionnaire to check their eligibility for TENS treatment and screen for any potential risks due to TENS. The experimental protocol was approved by the Institutional Review Board (IRB) of University of Maryland.

Experimental Setup

Customized equipment consisting of four one-dimensional force sensors was used to measure the maximal finger forces (Models 208 M182 and 484B, Piezotronics Inc., Depew, NY, USA). C-shaped aluminum thimbles were fixed at the bottom of each sensor in order to rest the distal ends of the fingers while pressing. The sensors were attached to an aluminum frame with four slits, allowing for the adjustment of sensor position based on the subject’s finger size. The subject’s hand were bent slightly at the metacarpophalangeal joint (MCP), proximal interphalangeal joint (PIP) and distal interphalangeal joint (DIP) in order to make a dome shape, when the fingers rested on the testing equipment (Figure 4.1).

The frame was tilted 25 degrees with respect to the anterior-posterior axis and attached to a vertical aluminum panel. This panel had a slit allowing for two degrees of freedom: vertical translation and rotation around the z-axis. During the experiment subjects pressed down on the C-shaped thimbles. The forces produced by the fingers were transmitted to the sensors. The signals from the sensors were set at 1000 Hz with a 16-bit A/D board (PCI 6034E, National

Instruments Corp., Austin, TX, USA) and were recorded by a software program created in LABVIEW (LabVIEW 7.1, National Instruments Corp., Austin, TX, USA). Force production data was transferred to a computer adjacent to the testing room. MatLAB (MatLAB 7, MathWorks, Inc, Natick, MA, USA) programs were written for data processing and analysis.

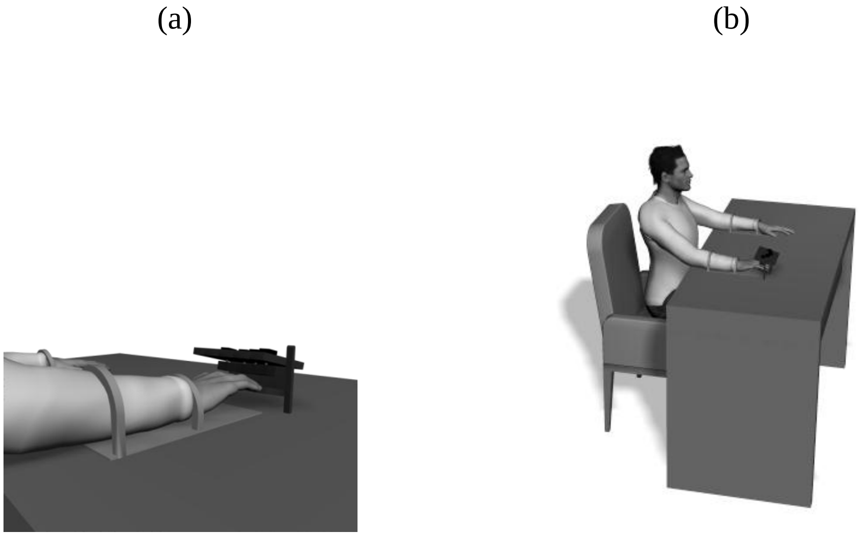


Figure 4.1 (a) Subjects were instructed to insert the distal phalanges of the fingers in the thimbles attached to a customized aluminum frame. (b) The wrists and the forearms of the subjects were rested in a wrist-forearm brace and held by Velcro straps.

Procedure

Five different finger combinations (four single-finger tasks and one four-finger task) for the MVF task were presented to the subjects. One trial was performed for each condition. The five conditions were presented to the subjects in a randomized order, with an interval of 3 min between consecutive pressing conditions. Once the subjects had comfortably positioned their fingers on their sensors, the investigators started the data collection program, which generated a “get ready” sound. This was followed by a “ding” sound after 2 s. Subjects were instructed to “press as hard as possible with the task finger and relax the fingers once they feel they cannot press any harder”. After 7 s, another audio cue in the form of a “ding” sound was presented to indicate the end of the trial. No visual feedback was provided to the subjects.

This process was repeated for three different experimental conditions. TENS was delivered via a portable unit (Elpha 3000 II, Danmeter A/S, biphasic, pulse width 200µs) with circular, self-adhesive electrodes on the distal phalanges of index, middle, ring and little finger. The intensity was self-selected by the participants and set to the maximum tolerable level. Data were collected on three different days at the same time of the day. The order of treatment conditions was randomly assigned to the subjects.

Data Processing

Maximum voluntary force (MVF) was measured as the peak forces produced by task finger or fingers during single-finger tasks and a four-finger task.

The force deficit for each finger was calculated by taking the difference of the maximum force produced by an individual finger in a single finger task and subtracting it from the force produced by the same finger in the four finger task.

$$\mathrm{FD}_i = F_{i,i} - F_{i,\mathrm{IMRL}} \tag{1}$$

Due to various factors, when a single finger is instructed to produce a force, the other fingers also produce and unintentional force. This phenomenon has been called finger independence. The average values of FI across all the four fingers were calculated as shown below (Equation 2).

$$\mathrm{FI} = 100 - \frac{{}_{j-1}^{n}[100\%*\ {}_{i=1}^{n}(F^{ij}/F^{i}_{max})/(n-1)]}{n} \tag{2}$$

Where$i \neq j$, n =4,$F^{i}_{\max}$ is the maximal force produced by the finger i, and $F^{ij}$is the involuntary force produced by the non-task finger i during the j finger MVF task.

Statistics

One-way repeated-measures ANOVAs were conducted to compare the MVF, FD and FI values between the three treatment conditions. The level of statistical significance was set at p=.05.

Results

Maximum Voluntary Force (MVF)

The MVF values for the single finger tasks increased significantly compared to the baseline condition for the index, middle and little fingers after 4Hz TENS treatment. Specifically, the MVF values increased 28% for the index finger (from 41.6±6.3N to 53.2±7.2N), 30% for the middle finger (from 39.9±5.2N to 49.2±6.3N) and 25% for the little finger (from 24.6±4.2N to 31.3±3.9N) (Figure 2A). No significant differences were observed for the ring finger task. Further, MVF values for the 110Hz condition were similar to the baseline condition during the individual finger tasks. These results were supported by ANOVA (Index: $F_{2,18}$ = 13.5; p<.01; Middle: $F_{2,18}$=5.83; p<.05; Little: $F_{2,18}$= 6.05; p<.05). For the four finger pressing task, MVF values were 30% greater than the baseline for 4Hz condition and 15% greater than the baseline for the 110Hz condition. MVF increased from 77.0±9.2N in the baseline condition to 89.0±11.6N in the 110Hz condition and 101.0±12.8N in the 4Hz condition (Figure 2B). The results were supported by ANOVA ($F_{2,18}$ = 8.94; p<.01).

Force Deficit (FD)

No significant differences in FD were found with TENS treatment.

Finger Independence (FI)

No significant differences in FI were found with TENS treatment.

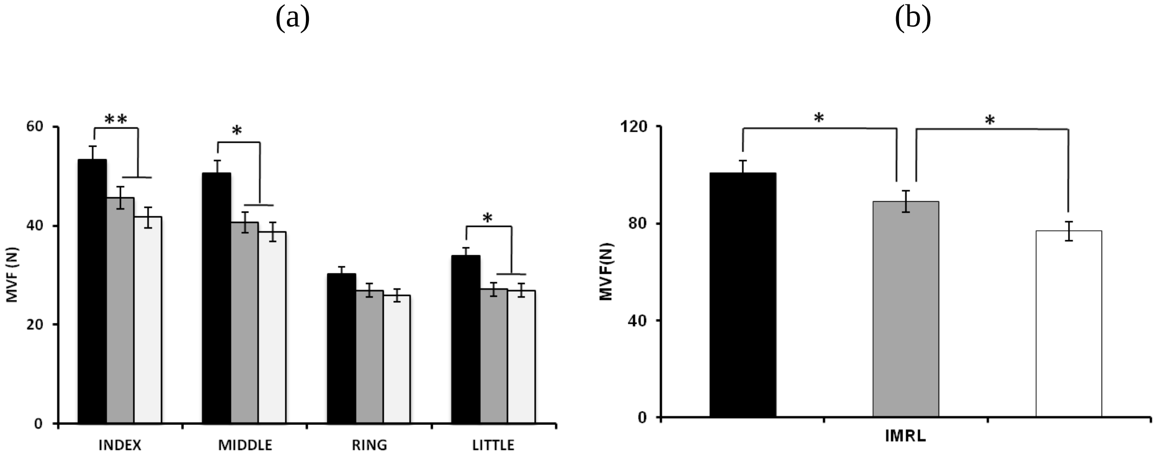


Figure 4.2(a) MVF in N, produces by individual fingers of the participants. (b) MVF in N for all the four fingers pressing together. Means and standard errors are shown across the subjects. The 4Hz TENS is represented in black, 110Hz in grey and baseline condition in white. (* = p<.05; ** = p<.01).

<u>Discussion</u>

Maximum voluntary force (MVF) production by the digits is vital to perform everyday activities and its importance is well documented in the literature [5, 14, 140]. Although TENS has typically been used as a modality of somatosensory stimulation to mitigate pain, the neurophysiological mechanisms of TENS are thought to excite the cortical motoneurons and affect motor output as well [44]. While low intensity, high frequency somatosensory stimulation is known to significantly affect the motor output in humans, animal studies have suggested low frequencies could achieve similar results [44, 108, 117, 141]. Therefore, this study was undertaken to investigate the effect of TENS treatment with low and high frequencies on MVF during multi-digit pressing. Participants described that the 4Hz condition gave them a “piercing” sensation, while the 110Hz condition gave them a “tingling” sensation.

Consistent with our hypothesis, MVF increased significantly with TENS treatment in comparison to the baseline condition. Specifically, 4Hz condition produced greater MVF as compared to the baseline condition and the 110Hz condition for index, middle and little fingers. No significant differences were observed for MVF in the ring finger among the three experimental conditions, although the data exhibited a similar trend of higher MVF values with 4Hz frequency. However, no changes in MVF were observed in individual finger tasks after 110Hz TENS treatment. In addition, 4Hz condition produced greater MVF for all the four fingers pressing together, followed by 110Hz and baseline condition respectively. 110Hz TENS treatment also produced greater MVF values than the baseline conditions for all the four fingers pressing together.

The experimental setup for this study afforded to stimulate the finger pads and had a minimal effect on the intrinsic or extrinsic muscles of the hand directly. Thus, changes in motor output due to neuromuscular stimulation, as observed in some previous studies [139], could therefore be ruled out in this study and the findings could be attributed to changes in somatosensory inputs alone. Previous studies providing visual or auditory feedback during maximum force production have shown a significant increase in force magnitude with the presence of appropriate sensory feedback [19, 58]. These studies suggest that under normal conditions, there is about 25-30% motor reserve which is not utilized typically and can be tapped into by using different methods like providing verbal motivation, visual or auditory feedback of force production.

Cutaneous feedback is known to be one of the major sensory modalities affecting the MVF production by the fingers of the hand [29, 137]. Although the exact neurophysiological mechanism of changes in cutaneous sensation with TENS is not yet known, it has been shown that TENS treatment could temporarily increase the cutaneous sensitivity [48]. TENS is thought to gate the somatosensory input at the peripheral level, through large afferent fibers and centrally through the cuneatus nucleus [47, 108]. There are four classes of low-threshold mechanoreceptors in human glabrous skin innervated by four classes of peripheral afferent nerve fibers. The neurons in the primary motor cortex have receptive fields in the periphery that receive inputs from the primary somatosensory cortex [20]. It is possible that low frequency TENS increased the cutaneous feedback, therefore changing the inputs to the primary somatosensory cortex, which in turn facilitate the inputs to the motor cortex, thus resulting in an increased motor output. These results are consistent with our recent study where MVF values decreased with the removal of cutaneous feedback [29].

Low frequency somatosensory stimulation of peripheral nerves has been known to increase the motor evoked potential as well as corticomotor excitability in previous studies [47, 49]. Results from this study suggest that the increase in motor output could depend on TENS frequency as well as the digits involved in the task. Increase in MVF after short term TENS treatment is consistent with results from such studies. The significant increase in MVF with short term TENS is encouraging and should be followed up with more elaborate studies to establish the most optimal combination of TENS parameters to obtain maximum motor output.

It is noteworthy that in most of the previous studies, high frequency TENS has been applied at sub threshold or threshold levels of detection [49]. In contrast, this study used high intensity TENS for both the 4Hz as well as the 110Hz condition. High frequency TENS at sub threshold intensity has been shown to produce significant improvements in hand motor performance. No changes in MVF for individual fingers observed in this study with 110Hz frequency suggest that the neurophysiological mechanisms involved in motor facilitation could change depending on the intensity of TENS and could be task dependent. It has been speculated that sub-threshold TENS enhances motor performance through the phenomenon called stochastic resonance [142-144]. However, at higher intensities of TENS, like those employed in the current study suggest a mechanism of motor facilitation that is completely different from stochastic resonance.

In conclusion, this study provides an important technique to enhance the MVF production capacity by employing low frequency, high intensity TENS.

Chapter 5: Surface texture plays a critical role in maximum finger force production

Abstract

The study investigates the role of surface texture on maximum voluntary force (MVF), finger force deficit (FD) and finger independence (FI). FD was calculated as the difference between the sum of maximal individual finger forces during single-finger pressing tasks and the maximal force produced by those fingers during an all-finger pressing task. FI was calculated as the average non-task finger forces normalized by the task-finger forces and subtracted from 100 percent. Ten young healthy right-handed males participated in the study. Surface texture was changed by pasting a 400 grit, low friction, smooth surface (SS) and a 40 grit, high friction, rough surface (RS) sand paper on the surface of the force sensors measuring the isometric forces produced by the digits. Subjects were asked to press force sensors with maximal efforts using individual digits as well as all four digits together, in the SS and RS conditions respectively. It was hypothesized that RS would provide enhanced afferent inputs from the cutaneous receptors, and facilitate the central commands responsible for the maximal force production. Contrary to our hypothesis, results from the study show a 20% higher MVF in the SS condition as compared to the RS condition. Further, FD values were 30% lower on average in the RS condition as compared to the SS condition. No significant changes in FI values were observed. It is suggested that the particle size of the SS closely matches those of Type 1 afferent fibers, and might have resulted in the selective activation of the same. This activation, in turn, could have facilitated the maximum motor output during finger pressing. In addition, change in FD with the two surface conditions suggests that the amount of neural drive changes disproportionally with surface texture, and this change depends on the number of fingers involved in the pressing task. No changes in FI suggest that the proportion of neural drive to different digit flexors does not change with the change in surface condition.

Introduction

The human hand is the primary effector by which we interact with the environment. Sensory feedback plays a vital role in conducting day to day manipulation tasks like pressing, grasping or pinching an object [96]. In particular, cutaneous feedback provides vital information about the shape, texture and temperature of the object in contact with the fingers [33]. This feedback is transmitted to the central nervous system (CNS) and is known to play a key role in accurate production of forces during sub-maximal force production tasks [20, 21, 31, 55]. In addition to sub-maximal force production tasks, studies have also shown that removal of cutaneous feedback significantly reduces the maximum voluntary force (MVF) production capacity of the fingers [33]. Further, the amount of friction between the fingers and the objects plays an important role during tasks involving grasping and prehension [3, 145]. The coefficient of friction between the fingers and the objects determines the amount of normal forces necessary to prevent the object from slipping, and the role of friction on grip force, pinch force and grasping force has been well documented in the literature [95, 146, 147]. While the role of surface texture has been investigated elaborately during the sub-maximal force production during tasks like pinching and grasping, the effect of surface texture on maximum force production by the digits is not yet known.

In recent years, multi-digit isometric pressing tasks have widely been used to investigate the motor behavior of the human hand [11]. In contrast to grasping and lifting tasks, which involve the thumb and require an accurate force ratio between the grip and load forces, pressing tasks provide a comparatively simpler experimental paradigm. The mechanical constraints that the CNS has to incorporate during pressing tasks are comparatively simpler as compared to the other tasks, and this task incorporates minimal involvement of tangential forces. In addition to investigating the MVF production during individual digit and multi-digit pressing, two other important variables have also been investigated in the literature. Finger independence (FI) is the measure of the extent to which the non-task fingers do not produce any force when the task finger is producing the MVF [25]. Finger force deficit (FD) has been defined as the difference in the MVF produced by a digit when it is pressing individually, as compared to the forces produced when all the four fingers are pressing together [26]. Both FI and FD are known to depend on the neural factors as well as anatomical factors [25, 26, 28].

A recent study on maximum isometric force production between the thumb and the index finger revealed that the normal force production of the fingers increases with the increase in the friction coefficient between the fingers and the manipulendum [3]. The neurons in the primary motor cortex have receptive fields in the periphery that receive inputs from the primary somatosensory cortex [148]. Glabrous skin covering the volar surface of the digits is highly specialized. There are four classes of low-threshold mechanoreceptors in human glabrous skin innervated by four classes of peripheral afferent nerve fibers [110]. The superficial Merkel complexes and Meissner corpuscles are innervated by slowly adapting type I afferents (SAI afferents) and fast-adapting type I afferents (FAI afferents), respectively. The deeper Ruffini organs and Pacinian corpuscles are innervated by slowly adapting type II (SAII) afferents and fast-adapting type II (FAII) afferents, respectively. Changes in cutaneous feedback are thought to be associated with the inputs to the primary somatosensory cortex [32]. Although studies investigating the change surface texture on sub-maximal force production tasks have shown significant changes in motor behavior, the role of surface texture on MVF production is not known.

The purpose of this study was to investigate the changes in MVF, FD and FI with the change in the surface texture of the pressing surface, during isometric pressing. Previous studies on removal or attenuation of cutaneous feedback have shown a decrease in MVF values, thus suggesting that afferent cutaneous feedback from the fingers facilitates the motor output [33]. Further, a more recent study has shown that during pinching, higher MVF is produced when the pressing surface has higher friction coefficient [3]. Therefore, it was hypothesized that the rough surface (RS) condition will provide an enhanced cutaneous feedback as compared to the smooth surface (SS) condition, and result in higher values of MVF. It was also hypothesized that changes in the surface texture will affect the efferent commands from the CNS and manifest as changes in FD and FI.

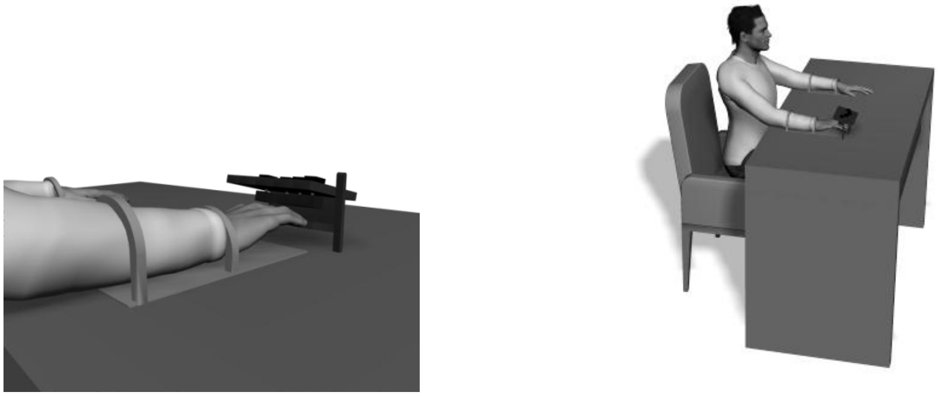
Methods

Subjects

Ten healthy volunteers (sex: 10 males, age: 21.57±1.50 years, body mass: 64.00±7.21 kg, height: 171.34±8.46 cm), with no history of neurological disorders, participated in the experiments. All the participants were right handed according to the criteria of Edinburgh handedness test. The hand length measured from the middle finger tip to the lunate of the wrist was 16.14±1.56 cm, and the hand width measured across the metacarpophalangeal (MCP) joints of the index and little fingers was 8.97±0.70 cm. All the participants gave informed consent based on the procedures approved by the Internal Review Board.

Experimental Setup

The experimental setup included four two-directional (tension and compression) force sensors for four fingers (2^{nd}–5^{th} fingers) with amplifiers (Models 208 M182 and 484B, Piezotronics, Inc.). The sensors were mounted on a customized aluminum frame (14.0 x 9.0 x 1.0 cm) and had parallel slits aligned vertically (14.0 cm). These slits enabled adjustments to the sensors according to the hand and finger sizes of the subjects. A C- shaped aluminum thimble was attached at the bottom of each sensor. Thimbles were placed at a fixed distance of 3cm in the mediolateral direction, such that the distal phalange of each finger could comfortably rest on an individual sensor (Figure 5.1). The thimbles were covered with sand papers of 40grit and 400grit to provide a high friction, RS and low friction, SS respectively. The average particle diameter of the 40 grit sand paper was 435 microns, while that of the 400 grit sand paper is 23 microns.



(a) (b)

Figure 5.1 (a) Subjects were instructed to insert the distal phalanges of the fingers in the thimbles attached to a customized aluminum frame. (b) The wrists and the forearms of the subjects were rested in a wrist-forearm brace and held by Velcro straps.

Signals from the sensors were conditioned, amplified, and digitized at 1,000 Hz with a 16-bit A/D board (PCI 6034E, National Instruments Corp.) and a custom software program made in LabVIEW (LabVIEW 7.1, National Instruments Corp.). A desktop computer (Dimension

4700, Dell Inc.) with a 19 in. monitor was used for data acquisition. Offline data processing was done using customized programs written in MatLab (MATLAB 7, MathWorks, Inc.).

Procedure

Subjects were asked to rest the distal phalanges of each of the four fingers of the right hand on a sensor such that all joints were slightly flexed and formed a dome shape with the hand (Figure 1a). The MCP joints were flexed at about 25°. Subjects were instructed to sit on a chair facing a computer screen, with the shoulder abducted 35° in the frontal plane and elbow flexed 45° in the sagittal plane. The forearm rested on the customized wrist-forearm brace (comprised of a piece of foam that was attached to a semi-circular plastic cylinder) fixed to a wooden panel (29.8×8.8×3.6) cm. Two Velcro straps, one near the wrist and the other near the elbow, were used to avoid any wrist joint or forearm movements. In order to remove the gravitational effects of the fingers, the force signals for the initial 0.5 s were averaged for each finger and subtracted from the later signals. Throughout the trials, subjects were instructed to keep their eyes open and focus the gaze on a point on the wall in front of them. No visual feedback in any form was provided.

Five different finger combinations (four single-finger tasks and one four-finger task) for the MVF task were presented to the subjects. One trial was performed for each condition. The five conditions were presented to the subjects in a randomized order, with an interval of 3 minutes between consecutive pressing conditions. Once the subjects had comfortably positioned the fingers on their sensors, the investigators started the data collection program and it generated a “get ready” sound. This was followed by a “ding” sound after 2 seconds. Subjects were instructed to “press as hard as possible with the task finger and relax the fingers once they feel they cannot press any harder”. After 7 seconds, another audio cue in the form of a “ding” sound was presented to indicate the end of the trial. It is to be noted that during the individual finger trials, all the four C-shaped thimbles were covered with the similar type of sand paper. No subject reported fatigue.

Data Processing

Maximum voluntary force (MVF) was measured as the peak forces produced by task finger or fingers during single-finger tasks and a four-finger task. The force deficit (FD) for each finger, FD_{i}, was calculated as the difference of the maximum force produced by an individual finger in a single finger task, $\mathrm{F}_{\mathrm{i,i}}$, and the force produced by the same finger in the four finger task, $\mathrm{F}_{\mathrm{i,\ IMRL}}$ (Eq. 1).

$$\mathrm{FD}_i = F_{i,i} - F_{i,\mathrm{IMRL}} \tag{1}$$

Normalized FD was calculated by dividing the FD values obtained for individual fingers in the two experimental conditions by those obtained in the low friction condition.

The average value of FI across all the four fingers was calculated as shown below (Eq. 2).

$$\mathrm{FI} = 100 - \frac{{}_{j-1}^{n}[100\% * \quad {}_{i=1}^{n}(F^{ij}/F_{max}^{i})/(n-1)]}{n} \tag{2}$$

Where$i \neq j$, n =4,$F_{\max}^{i}$ is the maximal force produced by the finger i, and $F^{ij}$is the involuntary force produced by the non-task finger i during the j finger MVF task.

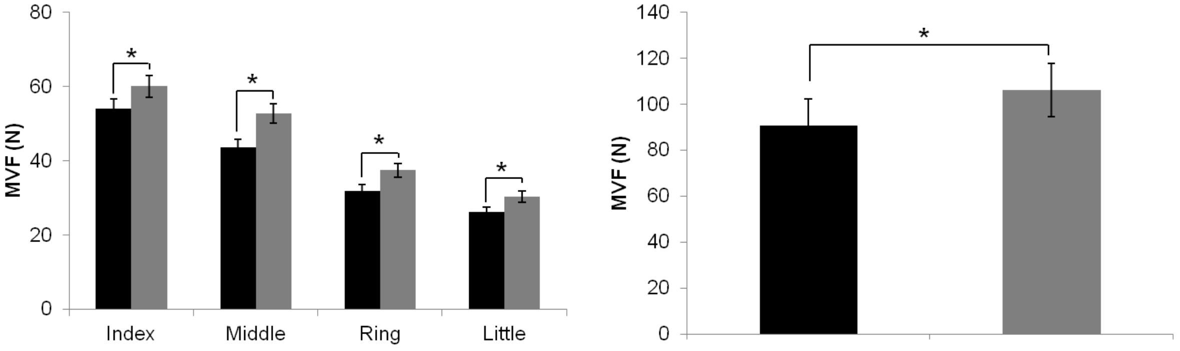
Statistics

One-way repeated-measures ANOVA’s were conducted to compare the MVF, FD and FI values between the two conditions, with and without anesthesia. The level of statistical significance was set at *p* = .05.

<u>*Results*</u>

Maximum Voluntary Force (MVF)

Maximum voluntary force (MVF) values were significantly higher in SS condition as compared to the RS condition for all the finger combinations. MVF increased from 54±6N to 60±5N for the index finger, from 44±5N to 53±6N for the middle finger, from 32±4N to 38±3N for the ring finger, 26±2N to 30±3N for the little finger and from 91±10N to 106±11N for all the fingers pressing together (Figure5.2a and b).



(a)

(b)

Figure 5.2 (a) MVF in N, produced by the individual fingers of the subjects in the RS condition (black) and SS condition (gray). (b) MVF values for four-finger task in RS (black) and SS condition (gray). Means and standard errors are shown across the subjects (*p<.05).

Increase in MVF values in the SS condition as compared to the RS condition were statistically significant for the individual fingers (Index: $F_{1,9}$ = 16.82, p<.05; Middle: $F_{1,9}$ = 20.34, p<.05, Ring: $F_{1,9}$ =27.35, p<.05, Little: $F_{1,9}$ = 30.21, p<.05) as well as the four-fingers pressing together ($F_{1,9}$ = 54.21, p<.05). Overall, the MVF values for all the finger combinations in the RS condition were about 10% less as compared to those in the LS condition.

Force Deficit (FD)

Force deficit (FD) was greater in the SS condition as compared to the RS condition (Figure 5.3). The increases in FD values were significant for all the four fingers (Index: $F_{1,9}$= 35.83, p<.01 Middle: $F_{1,9}$ = 20.29, p<.01; Ring: $F_{1,9}$ =27.29, p<.01, Little: $F_{1,9}$ =15.72, p<.01). FD value for the changed from 26±4N to 37±5N for the index finger, from 14±5N to 20±4N for the middle finger, from 9±3N to 15±4N for the ring finger and from 7±3N to 12±3N for the little finger.

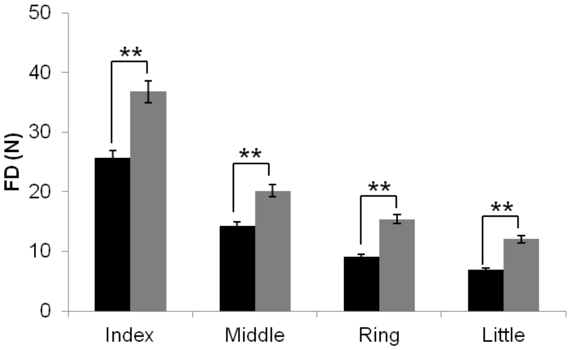


Figure 5.3 FD in N, calculated from single-finger tasks in the RS condition (black), and the SS condition (gray). Means and standard errors are shown across the subjects (**p<.01).

Finger Independence (FI)

No significant changes in FI values were observed between the two surface texture conditions (Figure 5.4).

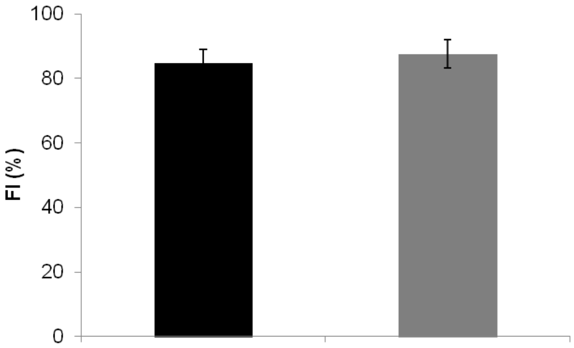


Figure 5.4 FI in N, calculated from single-finger tasks in the RS condition (black), and the SS condition (gray). Means and standard errors are shown across the subjects.

Discussion

The purpose of this study was to investigate the effect of surface texture on MVF, FD and FI. Contrary to our hypothesis, MVF was greater in the SS condition as compared to the RS condition. In addition, FD was greater in the SS condition as compared to the RS condition. However, no significant differences in FI were observed with the changes in surface condition.

Previous studies have suggested that tactile feedback from the digits modulates the motor output [36, 41]. The mechanism of changes in motor output due to changes in tactile feedback is thought to be mediated by the automatic reflex assistance due to the servo action of finger flexors involved during the task [36]. Increase of MVF in the SS condition corroborates the finding that the motor output could be affected by the changes in the cutaneous input, which in turn occurs due to the changes in surface texture. As compared to gripping task where the friction between the digits and the surface affects the normal force based on the load force of the object being held [20], the pressing task employed in the present study did not have such constraints. Therefore, the increase in MVF with the SS condition could be attributed to the changes in surface texture alone.

Contrary to our hypothesis, MVF was greater in the SS condition as compared to the RS condition. Glabrous skin of the hand is characterized by a thick epidermal layer, forming patterns of grooves and resulting in varied distribution of mechanoreceptors over the surface [149]. The particle size of the 400grit sand paper used for the LF condition is about 23 microns. This size closely matches that of the Type 1 mechanoreceptors [150]. Therefore, it is possible that the LF surface may have provided greater stimulation, and hence enhanced cutaneous feedback to the CNS. A characteristic feature of Type 1 mechanoreceptors is that they become more active as the intensity of the stimulus increases. It could be expected that MVF production task, like the one employed in the present study, could have stimulated these mechanoreceptors close to the maximum. In addition, about 50% of the mechanoreceptors belong to the Type 1 category, which is a sizeable number to produce the effect observed in this study.

Greater FD values in the LF condition also suggest the changes in the magnitude of motor commands. FD is thought to arise from the ceiling in the neural drive when multiple digits are producing MVF [26, 100]. Changes in FD suggest that the increase in the neural drive is greater when all the digits are pressing together, as compared to the individual digits. Although the observation of FD phenomenon in both the conditions confirms the ceiling hypothesis, changes in FD with the two surface conditions suggests that the amount of neural drive changes disproportionally for different digit combinations.

No changes in FI are consistent with the hierarchical model of digit control proposed in the literature [26]. This model suggests that the structure of motor commands is fixed at the central level, and changes at the peripheral level do not affect this structure. Consequently, the proportion of neural drive to different digit flexors does not change with the change in surface condition. It is worth noting that our recent in a recent study where the cutaneous feedback from the digits was removed by administering local anesthesia, no changes in FI values were observed [29]. Combined results from these two studies suggest that FI values are not affected by changes in cutaneous feedback from the digits.

In conclusion, this study provides the evidence of changes in MVF and FD with the change in surface texture. Simple dexterous tasks like grasping and pinching are a major challenge for patients with movement disorders as well as the elderly. Results from this study warrant further investigation in the role of surface texture on the maximum motor output in more ecologically valid tasks like grasping and pinching. Modulation of maximum motor output due to changes in cutaneous feedback, as observed in this study, may open avenues for enhanced motor performance, particularly in the sports that require maximum force production.

Chapter 6: Real-time visual feedback of finger forces modulates maximum finger force production

Abstract

The purpose of this study was to investigate the effect of real time visual feedback as well as visual feedback modulation on the maximum voluntary force (MVF), finger independence (FI) and finger force deficit (FD) during a multi-finger isometric force production task. Ten healthy, young, right handed male subjects participated in the study. In the baseline condition (BC), MVF from the individual fingers as well as the four fingers pressing together was recorded without any visual feedback. Following this, subjects were provided a target force recorded in BC, represented by a yellow horizontal bar on a computer monitor in three different conditions. The real time forces were represented by a red horizontal bar, which moved downwards towards the yellow bar when subjects pressed the force sensors. In the neutral condition (NC), the target force, represented by a yellow horizontal bar was equal to the maximum force produced by the subjects during the BC. In the easier condition (EC), the absolute value of the force seen on the screen remained the same as the BC; however, subjects were required to produce only 60% of the BC force to reach the yellow horizontal bar. On the other hand, the harder condition (HC) required the subjects to produce 140% of the BC force. Subjects were instructed to press as hard as possible, even if they cross the target force line and were unaware of force modulations. Results from the study show that the MVF values increased significantly with the presence of visual feedback. Further, MVF values were higher in the HC as compared to NC and EC. FI values decreased significantly with the presence of visual feedback. FD values increased significantly with the presence of visual feedback for the index and little finger, but not for the middle and ring finger. These results could be attributed to the adaptations in the motor commands originating from the central nervous system with the presence as well as modulation of visual feedback.

Introduction

The human hand is an excellent example of an effector capable of producing wide range of forces to conduct day to day manipulation tasks like pressing, grasping and rotating objects [96]. Although everyday activities typically involve sub-maximal force production, maximum voluntary force (MVF) by the fingers is known to be a predictor of quality of life [14]. In the last decade, multi-finger pressing has emerged as a practical paradigm to study the motor behavior of the hand. Several indices of finger interaction during multi-finger pressing have been well documented in the literature. It has been shown that when a single finger produces a maximum voluntary force (MVF), the other fingers produce an unintended force. This effect has been called finger enslaving or finger independence (FI) in the literature [27, 28]. It has also been shown that the maximum force produced by the individual fingers is greater than the maximum force produced when all of the fingers are pressing together. This phenomenon has been referred to as finger force deficit (FD) in the literature [26]. Both FI and FD are thought to depend on the central as well as peripheral factors, and provide an important window to investigate the changes in central and peripheral mechanisms related to isometric force production [12]. Studies investigating changes in these indices of finger interaction have suggested an adaptation hypothesis, which proposes that the decrease in MVF with factors like fatigue or aging results from similar adaptive changes in the central neural commands as well as the adaptations in the physical properties of the muscles. Further, it has been shown that FI and FD values increase aging as well as fatigue, although such changes in these indices of finger coordination could be the result of both, the changes in muscle properties as well as the changes in neural commands. As compared to aging or fatigue, providing sensory feedback is unlikely to change the material properties of the muscles involved during pressing, and any changes in MVF, FI and FD could be attributed to adaptations in neural commands alone. Although previous studies have investigated the changes in these variables with aging, fatigue and strength training, the effect of sensory feedback on MVF, FI and FD has not been investigated systematically.

Visual feedback is known to improve the motor performance in sub-maximal multi-finger isometric force production tasks [56, 121, 122]. Studies have shown that presenting the subjects with a real time visual feedback of the motor task performance during multi-finger isometric force production tasks results in lower force variability [122, 123]. Visual feedback is also known to improve motor performance in patients suffering with stroke and DCD, and is frequently used in rehabilitative paradigms [124]. A more recent study reported a change in muscular activity with the presence of visual feedback during a dexterous manipulation task, thus suggesting the presence of visual feedback could change the motor commands from the central nervous system (CNS) to the muscles [56].

Studies on isokinetic torque production have shown that presenting the subjects with a real time visual feedback and the target force could significantly increase their maximum torque generation capacity [58, 125, 126]. Studies on sedentary subjects measuring isokinetic torque production at the knee joints, as well as the quadriceps and hamstrings have shown a significant increase in the torque production capacity with the presence of online visual feedback (Larivière, Gagnon et al. 2009). Despite a number of studies investigating the role of visual feedback in sub maximal finger force production tasks and reports on increased isokinetic torque production in the presence of visual feedback, it is not known how the real time visual feedback affects the isometric MVF production by the fingers and the related inter-digital phenomena like FI and FD during isometric pressing.

The purpose of the present study is to investigate the effect of visual feedback and its modulation on MVF, FI and FD during a multi-finger pressing task in four conditions: baseline condition (BC), hard condition (HC), neutral condition (NC) and easy condition (EC). Based on the studies reporting and improved sub-maximal force production in dexterous manipulation tasks as well as increased maximum isokinetic torque production with the presence of visual feedback, the following hypothesis were tested:1. MVF would increase with the presence of visual feedback. 2. As compared to the NC, modulating the visual feedback, in the EC or HC would significantly increase the MVF.3. Based on the adaptation hypothesis, it was hypothesized that FI values would increase in the presence of visual feedback. Further, FI values would be greater In the EC and HC as compared to the NC. 4. Based on the adaptation hypothesis, FD values would decrease with the presence of visual feedback. In addition, FD values would be lower for the EC and HC as compared to NC.

Methods

Subjects

Ten healthy males (age: 21±3.3 years, body mass: 67.2±9kg, height: 1.69±0.25m), without any history of neurological disorders participated in the experiments. All of them were right handed according to the criteria of Edinburgh handedness test. All the subjects gave informed consent based on the procedures approved by the University of Maryland’s Internal Review Board (IRB).

Experimental Setup

For measuring the MVF, FI and FD, a device that has been used in most of the previous experiments on multi-digit pressing by our group was used [24]. Briefly, the device included four force sensors (for the four fingers), with amplifiers (Models 208 M182 and 484B, Piezotronics, Inc., Depew, NY, USA). The sensors were supported by a customized aluminum frame (14.0×9.0×1.0 cm) along four slits. The slits allowed adjustments of the sensor positions along the longitudinal axis of fingers according to the individual hand and finger sizes of the subjects. Adjacent slits were separated medio-laterally by 20 mm. The frame was attached to a large aluminum panel (21.0×16.0×2.0 cm) with a vertical slit (14.0 cm), which allowed the frame two degrees-of-freedom: one for vertical translation and the other for rotation about the Z-axis. C-shaped aluminum thimbles were attached on the bottom of each sensor, and the subject pressed down the thimbles, thus transmitting the forces to the sensors. The frame made and angle of 25° with respect to the antero-posterior axis (X-axis) such that all finger joints (distal inter-phalangeal, proximal inter-phalangeal, and MCP joints) were slightly flexed. By adjusting the positions of the individual thimbles along the slits, the frame was customized to fit in individual finger lengths. The frame was mechanically fixed to an aluminum panel using nuts and bolts (Figure 6.1a).

Signals from the sensors were conditioned, amplified, and digitized at 1,000 Hz with a 16-bit A/D board (PCI 6034E, National Instruments Corp., Austin, TX, USA) and a custom software program was made in LabVIEW (LabVIEW 7.1, National Instruments Corp., Austin, TX, USA). A desktop computer (Dimension 4700, Dell Inc., Round Rock, TX, USA) with a 19 inches monitor was used for data acquisition. MatLAB (MatLAB 7, MathWorks, Inc., Natick, MA, USA) programs were written for data processing and analysis.

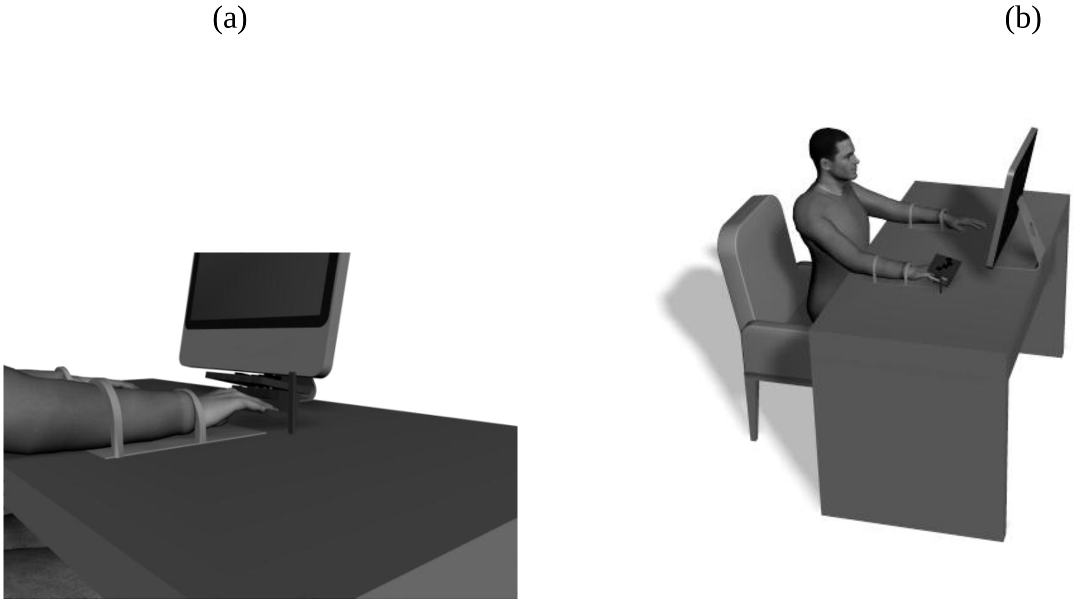


Figure 6.1 (a) Subjects were instructed to insert the distal phalange of each finger in the thimbles attached to a customized aluminum frame. (b) The wrists and the forearms of the subjects were rested in a wrist-forearm brace and held by Velcro straps. Subjects sat in a chair and watched the computer screen while performing the task.

Procedure

Subjects sat in a chair, facing the computer screen with their shoulders abducted at 35° in the frontal plane and the elbows flexed at 45° in the sagittal plane, making the forearm parallel to the aluminum frame. Subjects were instructed to insert all the four fingers in the thimbles. All joints of the fingers were slightly flexed and made a dome shape with the hand. The forearm rested on the customized wrist-forearm brace (comprised of a piece of foam that was attached to a semi-circular plastic cylinder) fixed to a wooden panel (29.8×8.8×3.6cm). Two Velcro straps, one near the wrist and the other near the elbow, were used to avoid any wrist joint or forearm movements. The MCP joints were flexed at about 25°. In order to remove the gravitational effects of the fingers, the force signals for the initial 0.5s were averaged for each finger and subtracted from the later signals. Thus, only the force signals due to active force production were shown on the computer monitor in real-time to subjects.

Data Processing

Maximum Voluntary Force (MVF)

For the BC, subjects performed five conditions of the MVF task in flexion with individual fingers as well as all the four fingers pressing together. During each trial, all fingers were inserted in the thimbles, and subjects were asked to produce maximum isometric force with a task finger(s) in flexion over a 7s interval. Three practice trials at five minute intervals were given before the actual data collection began. Following the practice trials, one trial was collected for each finger condition, with a resting period of three minutes between two consecutive conditions. Data was first collected in the BC and the order of task fingers was balanced across subjects. While pressing, subjects were instructed to fixate their vision on a point on the wall and keep their eyes open throughout the trial, since the subjects were also required to keep their eyes open in conditions with visual feedback.

Following the BC, subjects were presented with different visual feedback conditions in a randomized order. Three levels of visual feedback were presented to the subjects. In the NC, the baseline force, shown as a yellow horizontal bar on the screen represented the true value of the corresponding task finger MVF produced in the BC. The real time task finger force produced by the subjects was shown with a red horizontal bar, which moved in the downward direction towards the yellow bar when the subjects pressed the sensors. In the HC, the visual scale was modulated such that subjects had to produce 1.4 times the MVF recorded in the BC, in order to reach the yellow bar representing the baseline force. In the EC, the subjects had to produce 0.6

times the MVF in the BC in order to reach the yellow bar. As an example, if a subject produced 100N in the BC, the yellow line was always fixed at the 100N mark on the scale being presented on the screen. However, in the HC, subjects had to produce 140N in order to reach the yellow line, while in the "EC, they had to produce only 60N. It is to be noted that subjects were unaware of the modulation of the target force and the order of the conditions was randomized. Further, the subjects were instructed to "press as hard as possible with the task finger, even if they think they can go past the yellow bar".

In both the no feedback and visual feedback conditions, an auditory cue was given to the subjects, marking the beginning and ending of the trial. The experimenter watched the subjects' right hand carefully for any joint movements. Trials with visible finger or wrist joint movements were rejected (~1% of the total number of trials) and performed again by the subjects. The subjects were instructed to concentrate on the task finger and not to pay attention to the non-task fingers.

Finger Independence (FI)

Due to various factors, when a single finger is instructed to produce a force, the other fingers also produce and unintentional force. This phenomenon has been called finger independence [102, 151]. The average values of FI across all the four fingers were calculated as shown below (Equation 1).

$$\mathrm{FI} = 100 - \frac{{}_{j-1}^{n}[100\% * \ {}_{i=1}^{n}(F^{ij}/F_{max}^{i})/(n-1)]}{n}$$

(2)

Where $i \neq j$, $n = 4$, $F_{\max}^{i}$ is the maximal force produced by the finger i, and F^{ij} is the involuntary force produced by the non-task finger i during the j finger MVF task.

Force Deficit (FD)

The force deficit for each finger was calculated by taking the difference of the maximum force produced by an individual finger in a single finger task and subtracting it from the force produced by the same finger in the four finger task (Equation 2).

$$\mathrm{FD}_i = F_{i,i} - F_{i,\mathrm{IMRL}} \tag{1}$$

Statistics

The changes in MVF, FD and FI under different visual feedback conditions were statistically analyzed using repeated measures ANOVA. Two separate comparisons were performed. The level of significance was set at .05 for all the comparisons. Data was checked for violation of sphericity across levels of a within subject factor.

Results

Maximum Voluntary Force (MVF)

Amongst the individual finger pressing tasks, the MVF values increased significantly for the middle and little fingers with the presence of visual feedback (Table 6.1). The results were supported by ANOVA ($F_{1,9} = 56.5$, $P<.05$; $F_{1,9} = 6.3$; $p<.05$). Within the three visual feedback conditions, HC produced significantly higher MVF values in the little finger as compared to

Table 6.1 MVF in N, produced by index, middle, ring, little and all the fingers in different experimental conditions. Values within the parenthesis in the subscripts are not significantly different from each other. Mean and standard errors are shown across the subjects (* = p<.05; ** = p<.01).

	Maximum Voluntary Force (N)			
	BC	HC	NC	EC
Index	45±4.0	55±5.3	51±5.6	52±5.1
Middle*	$43\pm5.2_{(HC,NC,EC)}$	$52\pm5.3_{BC}$	$51\pm5.3_{BC}$	$53\pm4.7_{BC}$
Ring	34±7.1	36±3.5	34±4.7	33±5.6
Little*	$29\pm3.4_{HC,(NC,EC)}$	$37\pm6.3_{BC,(NC,EC)}$	$33\pm3.3_{BC,HC}$	$30\pm3.4_{BC,HC}$
All**	$101\pm11_{HC,(NC,EC)}$	$123\pm14_{BC,(NC,EC)}$	$119\pm12_{BC,HC}$	$116\pm10_{BC,HC}$

Values are mean ± *SE* (standard error) across all subjects.

NC and EC. MVF values were also significantly greater for all the four fingers pressing together. The results were supported by ANOVA ($F_{3,9} = 15.3$; p<.05). Within the three visual feedback conditions, the HC produced significantly higher forces in the four fingers pressing task compared to NC and EC. The results were supported by ANOVA ($F_{2,9} = 5.5$; p<.05; $F_{3,9} = 20.26$; p<.01).

Force Deficit (FD)

No significant differences were observed in the FD values within the BC and visual feedback conditions for the middle and the ring fingers (Figure 6.4). However, for the index finger, FD in the BC was significantly lower than the FD in the HC, NC or EC. The results were supported by ANOVA ($F_{3,9} = 7.65$; $p < .05$). FD in the ring finger for the HC was significantly greater than that in the BC, NC and EC. The results were supported by ANOVA ($F_{3,9} = 12.29$; $p < .05$)

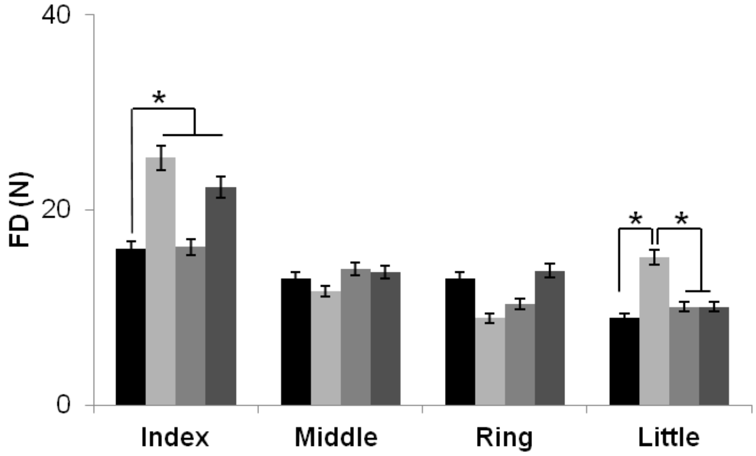


Figure 6.3 FD in N, for the individual fingers of the subjects in the BC, HC, NC and EC. Black color represents BC, light grey represents HC, grey represents NC and dark grey represents EC respectively. Mean and standard errors are shown across the subjects (* = p<.05).

Finger Independence (FI)

The values of FI were 5% greater in the no feedback condition as compared to the visual feedback condition (Figure 6.3). FI was also 5% higher in the HC and NC, as compared to the EC. FI values for the BC were 10% higher than the EC. The results were supported by ANOVA ($F_{3,9} = 5.76$; $p < .05$).

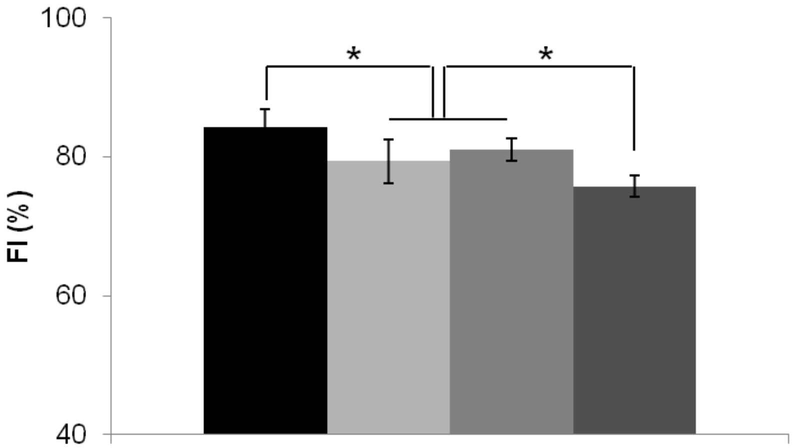


Figure 6.3 FI values in the BC, HC, NC and EC. Black color represents BC, light grey represents HC, grey represents NC and dark grey represents EC respectively. Mean and standard errors are shown across the subjects (* = p<.05).

Discussion

The purpose of this study was to investigate the effect of real time visual feedback and modulation of visual feedback on MVF, FI and FD during a multi-finger isometric force production task. Results from the study revealed that presenting the subjects with a real time visual feedback significantly increased the MVF production for middle, little and all the four fingers pressing together, thus confirming our first hypothesis. Further, MVF values were significantly greater in the HC as compared to the NC or EC, thus confirming our second hypothesis. In confirmation with our third hypothesis, FI values significantly decreased with the visual feedback. As opposed to our fourth hypothesis, FD did not change with the presence of visual feedback for the middle and ring fingers, but increased significantly for the index and little fingers

Isometric MVF has been used as a prominent measure of static strength and is known to depend on factors like motivation, stress levels, physical properties of the muscles as well as tactile feedback [56, 57, 152]. While very few studies have been conducted to investigate the changes in MVF during multi-finger isometric force production tasks with these factors, visual feedback, in particular has frequently been reported to increase the isokinetic torque production [153]. Results from the present study are consistent with the findings from such studies conducted on isokinetic force production tasks.

The experimental design of the present study ensured that the biomechanical factors are minimally affected. Therefore, increase in MVF with the presence of visual feedback could be attributed to the changes in motor commands emanating from the CNS alone. Studies on sub-maximal isometric force production have shown that in the absence of tactile feedback, visual feedback plays an important role in producing accurate forces[122]. However, it is not yet clear if the compensatory mechanism involving visual feedback during sub-maximal tasks and maximal force production task is similar. Previous studies on maximum torque production in isokinetic tasks have reported a significantly improved performance when subjects are verbally motivated or psychologically aroused [59, 65, 152]. In addition, a similar increase in MVF as observed in this study has been reported with strength training of the fingers. However, as opposed to strength training where both neural as well as morphological adaptations take place, the experimental design of this study eliminates any changes in the muscular adaptations of the muscles. Hence, the increase in MVF observed in this study could be attributed to the increase in the magnitude of motor commands alone. It is beyond the scope of the current study to identify the mechanism responsible for the increase in MVF with the presence and modulation of visual feedback, but it is likely that these changes could be mediated by the motivation levels of the participants. Changes in MVF could also be attributed to the changes in perceived finger force production, although this effect was not measured in this study and needs to be investigated further [154]. Regardless of the mechanism, results from this study suggest that the CNS has the capacity to significantly increase the magnitude of motor commands irrespective of the physical properties of the muscles.

It is well established that both aging and fatigue reduce the MVF production capacity during multi-finger pressing, and these changes have been attributed to both, a reduction in the magnitude of motor commands as well as changes in the physical properties of the muscles. In light of the results from this study, it might be possible to increase the MVF values during aging and fatigue, providing important implications for rehabilitation as well as motor performance. While the central mechanisms for sub-maximal and maximal force production tasks could be very different, results from this study show that the motor system has the capacity to generate significant higher forces with the presence of visual feedback, and these changes in forces are modulated by the changes in motor commands.

The observation that FI decreases significantly with the presence of visual feedback points to the fact that the distribution of motor commands affecting FI changes with visual feedback as well as visual feedback modulation. These changes in FI with the changes in visual feedback could be attributed to adaptations in the distribution patterns of motor commands or the recruitment patterns in the muscles involved during individual digit pressing. The results are consistent with a previous study which showed that removal of visual feedback could alter the muscular activity during isometric contractions [56].

Many previous studies investigating multi-digit synergies have used a similar visual feedback protocol in order to measure FI. However, the size of the computer monitor and the amount of distance moved by the bar in the vertical direction has not been standardized during such studies, and it was assumed that the FI values remain unaltered. Results from the current study do not support this assumption, and in order to compare the data on multi-digit synergies in the mode space across different studies, standardization of visual feedback is recommended.

In conclusion, results from this study suggest that that the MVF production capacity during isometric pressing could significantly be increased by providing appropriate real time visual feedback. Further, FI and FD values change with the modulation of visual feedback, thus reinforcing the idea that apart from the biomechanical factors, FI and FD are regulated by the central commands.

Chapter 7: Fifteen minute exposure to high intensity light increases maximum finger force production

Abstract

Ambient light has commonly been associated with the emotional state of individuals, and is known to affect the motor performance in multi-digit, sub maximal force production tasks. However, the role of ambient light on maximum voluntary force (MVF) production, finger force deficit (FD) and finger independence (FI) is not clearly known. The purpose of this study is to investigate the effect of ambient light conditions on MVF production, FD and FI during multi-digit isometric pressing tasks. 10 healthy, young subjects (5 males and 5 females) were instructed to press one dimensional force sensors with their index, middle, ring, little or all the four fingers pressing together. Ambient light conditions were adjusted to three levels – no light condition (0-5Lux), normal light baseline condition, (500 Lux) and high light (5,000 Lux) condition. Participants were exposed to a given ambient light condition for fifteen minutes, and a visual analog scale was administered to assess their emotional state after the exposure. This was followed by force production tasks. Results from the study show a 20% increase in MVF for index and middle finger tasks in the high light intensity condition as compared to the normal or dark conditions. In addition, when participants were instructed to press with all the four fingers together, MVF was greatest in the high light intensity condition, followed by the normal light condition and the dark condition respectively. Results from the visual analog scale revealed no changes in the eight emotional states of the participants with light exposure. Further, no significant differences in FD or FI were observed. These results suggest that while the magnitude of neural drive increases significantly with short term exposure to high intensity light, this change is not mediated by the emotional states of the participants. In addition, no changes in FD and FI suggest that only the magnitude but not the distribution of the motor command to the fingers changes with the increase in light intensity.

Introduction

Sensory feedback plays a major role in the successful execution of activities of daily living [20, 109]. Tactile, proprioceptive, visual and auditory feedback are the primary modalities by which the Central Nervous System (CNS) obtains feedback from the environment [155]. The role of these feedback mechanisms has extensively been studied for tasks like postural control , locomotion and grasping [21].

In addition to the sensory feedback, the emotional state of the subjects has also been linked to their motor performance [152]. It has been shown that subjects are able to produce higher MVF during an isometric elbow flexor task when they are verbally motivated. The relationship between force production and the connotation of the words being used to motivate the subjects has also been examined. In one of such experiments, MVF increased by 5% when subjects were verbally encouraged [152]. Another study that examined the effect of the amplitude of verbal instruction reported that MVF increased as the amplitude of verbal instruction increased [156]. These studies suggest that apart from the biomechanical properties of the muscles or the sensory feedback available to the effectors, the MVF production could also depend on the emotional state of the subjects [10, 157].

When examining the effect of emotional stimuli on force production, varying results have been reported in the literature. Studies have shown that regardless of emotional state, pleasant or unpleasant, there is an increase in the maximum force production. In one such study, emotional state was manipulated by using 20 digitized photos obtained from the International Affective Picture System [60]. These images were selected according to their affective normative rating, matching arousal between pleasant and unpleasant images and differentiating these images from neutral images. Other studies have found that negative emotional stimuli have a greater effect on increasing force production than positive emotional stimuli [59].

It has been reported that ambient light affects the arousal levels of individuals, which in turn is linked to the changes in motor performance [62, 127, 128]. Dimly lit work environments reduce the arousal levels, while it improves as ambient light increases to a specific point [62, 64]. Because of its emotion altering abilities, ambient light has frequently been used to treat seasonal depression and epilepsy [127-129]. Furthermore, a positive emotional state has been associated with successful motor task performance during sub maximal force production tasks. People in positive emotional states have the ability to focus their attention fully on the task and thus perform the task at hand more successfully [61, 130]. Exposure to emotional state changing stimuli is known to interfere with movement that requires greater attentional resources [61]. Studies have also shown that while performing simple motor tasks, such as pinching, stimuli arousing both positive as well as negative emotions impair performance, however the decline in motor performance is more drastic when the stimulus arouses a negative emotion [131].

The human hand is the primary effector through which we interact with the environment [20, 41, 158]. Tasks such as pressing, prehension, grasping and pinching require accurate production of forces and torques by various fingers and extensively rely on the sensory feedback [20, 21, 159, 160]. The role of sensory feedback on sub-maximal task production is well documented in the literature. It has been shown that loss of cutaneous, proprioceptive and visual feedback results in more errors during multi-digit force production tasks [37, 110, 112], while providing an visual or auditory feedback for the multi-digit force production improves the task performance [97]. However, there are very few studies that have investigated the role of sensory information on maximal voluntary force (MVF) production. Two additional variables that have frequently been reported in studies related to the motor performance of the human hand are force deficit (FD) and finger independence (FD). Both FD and FI are known to depend on both central as well as the biomechanical factors, although the exact mechanisms for these phenomena are not yet known. However, if the biomechanical factors are not manipulated, changes in FD and FI could provide important insights into the changes at the level of motor commands from the CNS.

The purpose of this study is to investigate the changes in MVF, FD and FI with the changes in ambient light intensity. Ambient light has commonly been associated with the emotional state of individuals, and is known to affect the motor performance in multi-digit, sub maximal force production tasks. It is well reported that ambient light affects the emotional state of individuals, which in turn is linked to the changes in motor performance. Previous studies have shown that presenting a positive emotional stimulus to the participants significantly increases their force production capacity during isokinetic tasks [61, 65]. This suggests that high arousal level increases the magnitude of motor commands, resulting in higher forces. Since high light intensity is known to produce positive emotional states in individuals, it is hypothesized that participants will produce significantly greater amount of MVF when exposed to high intensity light as compared to the normal light intensity. Conversely, it is expected that the MVF would be significantly lower when participants are exposed to no light, as compared to the normal light condition.

Methods

A within subject design was employed with ambient light intensity being the independent variable. Ambient light levels were measured in Lux and subjects were exposed to three different levels of ambient light – dark condition (0-5 Lux), normal light intensity condition (500 Lux) and high light intensity condition (5000 Lux). MVF, FD and FI, all measured in Newton will be the dependent variables.

Subjects

Ten healthy, young subjects (5 males and 5 females; age: 21.0±2.0 years), participated in the experiment. These individuals were screened for any history of neurological disorders and were right handed according to the criteria of the Edinburgh handedness test. The Edinburgh handedness test consists of a questionnaire listing various activities in which subjects must indicate which hand they generally used to complete the task. The experimental protocol was approved by the Institutional Review Board (IRB) of University of Maryland.

Experimental Setup

Customized equipment consisting of four one-dimensional force sensors was used to measure the maximal finger forces (Models 208 M182 and 484B, Piezotronics Inc., Depew, NY, USA). C-shaped aluminum thimbles were fixed at the bottom of each sensor in order to rest the distal ends of the fingers while pressing. The sensors were attached to an aluminum frame with four slits, allowing for the adjustment of sensor position based on the subject's finger size. The subject's hand were bent slightly at the metacarpophalangeal joint (MCP), proximal interphalangeal joint (PIP) and distal interphalangeal joint (DIP) in order to make a dome shape, when the fingers rested on the testing equipment (Figure 7.1).

The frame was tilted 25 degrees with respect to the anterior-posterior axis and attached to a vertical aluminum panel. This panel will have a slit allowing for two degrees of freedom: vertical translation and rotation around the z-axis. During the experiment subjects pressed down on the C-shaped thimbles. The forces produced by the fingers were transmitted to the sensors. The signals from the sensors will be set at 1000 Hz with a 16-bit A/D board (PCI 6034E, National Instruments Corp., Austin, TX, USA) and were recorded by a software program created in LABVIEW (LabVIEW 7.1, National Instruments Corp., Austin, TX, USA). Force production data was transferred to a computer adjacent to the testing room. MatLAB (MatLAB 7, MathWorks, Inc, Natick, MA, USA) programs were written for data processing and analysis.

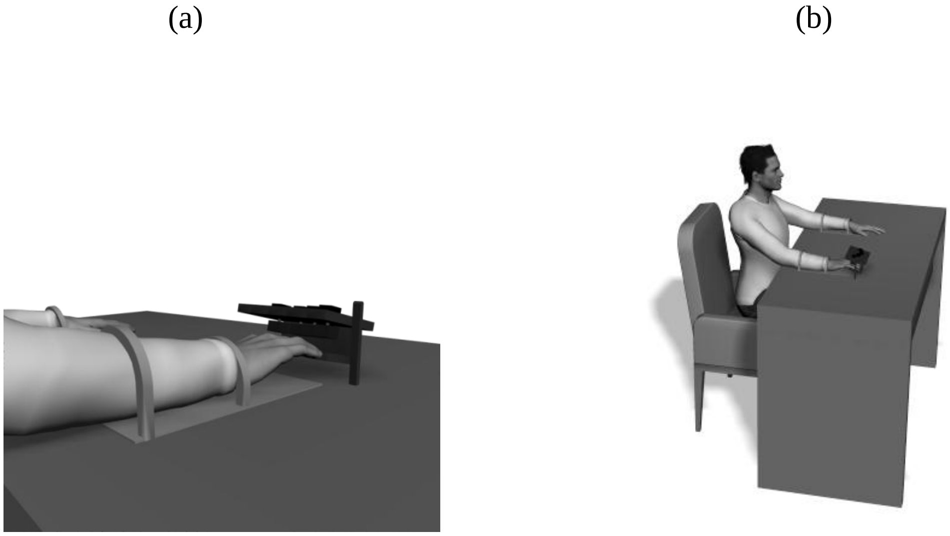


Figure *7*.1 (a) Subjects were instructed to insert the distal phalange of each finger in the thimbles attached to a customized aluminum frame. (b) The wrists and the forearms of the subjects were rested in a wrist-forearm brace and held by Velcro straps.

Procedure

During the experiment, subjects sat in a chair with their arms resting on the table. The subjects were instructed to place their right forearm in a brace parallel to the aluminum frame that will hold their fingers in the sensors, while their left arm will remain unrestrained on the table top. Subjects were instructed to produce maximum isometric forces with individual fingers and all fingers together in three ambient light conditions. The light intensity was measured at the face of the subject. The order of exposure to the three light intensity conditions and task-finger were randomized across subjects. Each trial was seven seconds long and an audio cue will be given to the subjects by the computer program indicating the beginning and end of each trial. After exposure to each light condition, subjects were asked to fill a Visual Analog scale to assess their affective state across the following eight emotions: anger, energy, tiredness, happiness, tenseness, fear, confusion and sadness. Raw scores from the visual analog scale were converted to the standardized scores using the tables provided with the scale. These scores were then used to compare the changes in affective state with light intensity. Subjects sat alone in the testing room and the data collection computer was operated from an adjacent room. A large glass window, covered by a thick black curtain separated the two rooms and prevented any light or sound from entering into the data collection room.

Data Processing

Maximum Voluntary Force (MVF)

In all trials, the same audio cue notified the subjects to begin the pressing task. This audio recording will first instruct the subjects to get ready and then shortly follow with a “ding” sound, signaling subjects to begin the pressing task. After seven seconds, subjects heard another “ding” sound, informing them that the trial has ended. Force sensors recorded the forces produced by all fingers in each of the trials. Subjects were given 3 minutes of rest in between each of the five trials to prevent fatigue. Subjects were told to keep their eyes open for all the trials and fix their gaze on a point on the wall opposite to them.

Force Deficit (FD)

The force deficit for each finger was calculated by taking the difference of the maximum force produced by an individual finger in a single finger task and subtracting it from the force produced by the same finger in the four finger task.

$$\mathrm{FD}_i = F_{i,i} - F_{i,\mathrm{IMRL}} \tag{1}$$

Finger Independence (FI)

Due to various factors, when a single finger is instructed to produce a force, the other fingers also produce and unintentional force. This phenomenon has been called finger independence. The average values of FI across all the four fingers were calculated as shown below (Equation 2).

$$\mathrm{FI} = 100 - \frac{\sum_{j-1}^{n}[100\% * \sum_{i=1}^{n}(F^{ij}/F_{max}^{i})/(n-1)]}{n} \tag{2}$$

Where$i \neq j$, n =4,F_{max}^{i} is the maximal force produced by the finger i, and $F^{ij}$is the involuntary force produced by the non-task finger i during the j finger MVF task.

Statistics

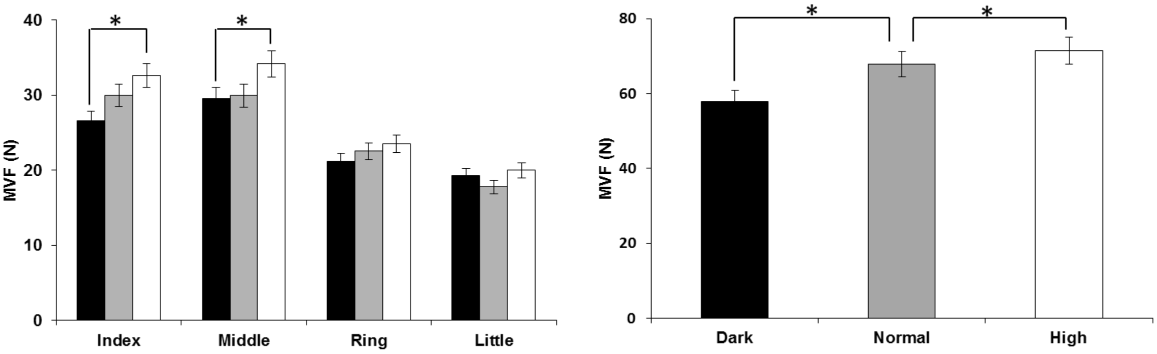
A one-way within factors ANOVA was conducted to compare the MVF, FD, FI and standardized scores from the visual analog scale in the three different experimental conditions. The alpha values were set at .05.

Results

Maximum Voluntary Force (MVF)

In the single-finger pressing tasks, MVF was found to be significantly greater for the index and middle fingers in the high intensity light condition as compared to the no light condition. Specifically, MVF decreased from 32.6±3.9N to 26.5±3.2N for the index finger and from 34.1±3.7N to 29.5±2.9N for the middle finger.

The results were supported by ANOVA. For the four-finger pressing task, MVF values were the lowest for the no light condition, followed by the normal light intensity condition and the high light intensity condition respectively. MVF increased from 57.9±7.2N in the dark condition, to 67.5±6.4N in the normal light intensity condition and 71.3±6.3N in the high light intensity condition. The results were supported by ANOVA.



(a)

(b)

Figure 7.2 (a) MVF in N for individual fingers and (b) all the four fingers. No light condition is represented in black, normal light in grey and high light intensity condition in white. Means and standard errors are shown (* = p<.05).

Force Deficit (FD)

No significant differences in FD were observed with the change in ambient light intensity.

Finger Independence (FI)

No significant differences in FI were observed with the change in ambient light intensity. In addition, no changes in the VA scores for the eight emotional states were observed.

Discussion

The purpose of this study was to investigate the changes in MVF when the ambient light conditions were changed during a multi-digit pressing task. MVF values increased significantly with the exposure to high intensity light and decreased significantly with the exposure to no light for the index, middle and all the four fingers pressing together.

The effect of emotional stimulation on movement is known to depend on the direction of the intended movement. Unpleasant emotions activate the defensive circuitry, readying withdrawal behaviors and causing movements directed away from the body. On the contrary, pleasant emotions activate the appetitive circuits which prepare approach behavior and result in movements towards the body [161, 162]. Previous studies have shown that exposure to unpleasant visual stimuli increase MVF production more so than pleasant and neutral stimuli. In this study, force productions of the wrist and finger extensor muscles were measured during a wrist extension task. This movement was classified as an avoidance behavior because the limbs were moving away from the body; the defensive circuitry was further activated during the exposure to negative stimuli, thereby increasing force production during this condition [59]. Sub maximal force production pressing tasks are used in day to day life for performing nonthreatening tasks like typing, playing the piano or opening the door of the car. It is possible that a positive emotional state, simulated by the bright ambient light, increases the force production.

Another study examined the impact of emotional state on force production but focused on a precision pinch grip task that was not directed towards or away from the body. In this case, both positive emotional stimuli, erotic images, and negative emotional stimuli, mutilation images, increased force production in the same manner [60]. Additionally, studies have suggested that a positive emotional state allows subjects to better focus their attention on the task at hand, resulting in more successful motor performance than when subjects are in a negative emotional state [61]. Attentional control, which is highly influenced by emotional stimuli, is very important during the motor planning process. Visual and cognitive information from the surrounding environment are combined with memories of past movement experiences to select the appropriate motor response[163]. Therefore, working memory is essential to motor planning. Because of this, even simple motor behaviors, such as a multi digit pressing task, are susceptible to interference from the attentional system. Results from our study did not reveal any changes in the eight affective states of the participants, although it is worth noting that the visual analog scale is very subjective and we did not measure changes in the stress as well as attention levels of the participants.

Emotional information is received by the motor cortex by the thalamus and consequently effects the force production of the muscles [60]. It has been found that force production increases when subjects are exposed to unpleasant or pleasant images as opposed to neutral images [65]. It has been suggested that emotional stimuli, regardless of severity or type increases perceptual processing resources, and thus alter peripheral reflexes. The motor cortex is excited by emotional stimuli, as compared to neutral or no stimuli [164]. Emotional stimuli also prime the motor cortex, preparing the body for action.

Results from this study show that in addition to tactile, proprioceptive and visual feedback, ambient light condition could significantly change the force production capacity of the human body. These results could have important implications to improve motor performance both, in rehabilitation settings as well as to improve athletic performance.

Chapter 8: Summary of conclusions

Results from the five experiments presented in this dissertation have been summarized in Table 8.1. The major conclusions from these studies are as follows:

1. The change in the magnitude of MVF depends on the type of sensory feedback provided to the participants. Using the appropriate sensory feedback condition, participants were successfully able to tap into their motor reserve and increase the MVF by as much as 25% of their baseline MVF.
2. FD and FI also depend on the type of sensory feedback provided to the participants. Since the biomechanical factors in these experiments were not manipulated, these changes in FD and FI could be attributed to neural factors alone.
3. FD and FI are mutually independent and represent two different neurophysiological phenomena. Both tactile as well as visual feedback resulted in changes in FD and FI.
4. Results from these experiments suggest that tactile feedback affects MVF, FD and FI by the involvement of spinal level entities, while visual feedback is speculated to involve supra-spinal entities.
5. Results from these experiments call for a more standardized experimental protocol for studies on multi-digit pressing. Conditions like resolution of the monitor for visual feedback, ambient light intensity and texture of the pressing surface should all be standardized in order to compare the results across different studies on multi-digit pressing.

Table 8.1: Summary of results

	Maximum Voluntary Force (MVF)	**Force Deficit (FD)**	**Finger Independence (FI)**
Anesthesia	Decreases by 25% after administration of anesthesia	Increases by more than 50% after administration of anesthesia	No change
TENS	Increases by 20% with low frequency, high intensity TENS	No change	No change
Surface texture	Increases by 15% with smoother surface texture	Increases by 40% with smoother surface texture	No change
Real time visual feedback	Increases by 20% with the presence and modulation of visual feedback	Increases by 20% with the presence and modulation of visual feedback	Decreases by 10% with the presence and modulation of visual feedback
Ambient light intensity	Increases by 15% with high light intensity and decreases by 10% with no light	No change	No change

Chapter 9: General discussion

This purpose of this dissertation was to investigate the role of tactile and visual feedback on MVF, FD and FI during multi-finger pressing. The series of experiments presented in this dissertation revealed that healthy adults have a capacity to produce much greater MVF, given the appropriate sensory feedback conditions. Specifically, stimulating the cutaneous receptors by means of TENS, or changing the texture of the pressing surface resulted in up to 25% increase in MVF during pressing. Further, removing the cutaneous feedback by means of digital anesthesia resulted in a 40% decrease in MVF. Furthermore, presenting the participants with a real-time visual feedback of the pressing forces or exposing them to high intensity light conditions for 15 minutes also increased the MVF production by up to 25%.

In addition to MVF, FD and FI changed in some experiments while no significant differences were observed in the others. Previous studies have observed significant differences in FD and FI due to aging, strength training and fatigue [10, 12, 43]. However, all these phenomena involve morphological changes as well as neural adaptations, and results from previous studies could not distinguish between the neural and physiological contribution to FD and FI. Results from this dissertation show that firstly, both FD and FI can change with short term neural adaptations even though no physiological changes occur in the neuromuscular system, and secondly, these neural adaptations possibly involve different sensory pathways depending on the sensory feedback being presented to the subjects.

MVF production is an important marker for strength, and is extensively used in clinical settings [14]. In addition, maximum isokinetic torque production tasks are extensively used in sports performance, although the role of sensory feedback during such tasks has not been investigated extensively. On one hand, results from this dissertation raise important questions about the neurophysiological mechanism responsible for MVF, FD and FI. On the other hand, these results warrant further investigation of the role of sensory feedback in clinical populations for the purpose of rehabilitation, as well as in elite athletes for enhancing their performance. Keeping these two goals in mind, the following follow up experiments are suggested:

1. Studying the combined effects of TENS frequencies, duration, amplitude, wave form as well as surface texture and investigating the interactions between these variables.
2. Studying the combined effects of real-time force feedback and ambient light condition, and investigating the interactions between these variables.
3. Studying the effect of different sensory modalities in dynamic force production tasks like power lifting among elite athletes.
4. Studying the effect of different sensory modalities in conjunction with Transcranial Magnetic Stimulation (TMS) to establish if manipulating these sensory feedbacks enables elite athletes to reach their maximal neural drive. In addition, employing TMS to establish if changes in tactile feedback are mediated by spinal reflexes or cortical processes.
5. Studying the effect of visual feedback in conjunction with Electroencephalogram (EEG) and functional Magnetic Resonance Imaging (fMRI) in order to measure affective state of the participants when the visual feedback is manipulated.
6. Studying the effect of cutaneous feedback removal from the dominant hand and conducting a force matching task with the non-dominant hand in order to clarify the role of perception of forces in MVF reduction, as compared to loss of cutaneous feedback alone.

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