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Neuromotor Control of the Hand During Smartphone Manipulation

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NEUROMOTOR CONTROL OF THE HAND DURING SMARTPHONE MANIPULATION

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sEMG:	Surface Electromyography
iEMG/time:	Integrated EMG/time
MCOND:	Movement Condition
CWSD:	Comfortable Walking Speed with Device
CWS:	Comfortable Walking Speed without Device
AMI:	Amplitude Modulation Index (AMI)
FDI:	First Dorsal Interosseous
APB:	Abductor Pollicis Brevis
ADM:	Abductor Digiti Minimi
FCR:	Flexor Carpi Radialis
ECU:	Extensor Carpi Ulnaris
EPL:	Extensor Pollicis Longus
ED:	Extensor Digitorum
ADEL:	Anterior Deltoid
MDEL:	Medial Deltoid
PDEL:	Posterior Deltoid
RTRAP:	Right Trapezius
LTRAP:	Left Trapezius
LR:	Left to Right
RL:	Right to Left
NW:	NorthWest
SE:	SouthEast

NE:	NorthEast
SW:	SouthWest
ST:	Single tap
MT:	Multi-tap
MCPI:	Metacarpophalangeal of the Index Finger
COV:	Coefficient of Variation
ABD:	Abdomen
SHD:	Shoulder

ABSTRACT

The primary focus of this dissertation was to understand the motor control strategy used by our neuromuscular system for the multi-layered motor tasks involved during smartphone manipulation. To understand this control strategy, we recorded the kinematics and multi-muscle activation pattern of the right limb during smartphone manipulation, including grasping with/out tapping, movement conditions (MCOND), and arm heights.

In the first study (chapter 2), we examined the neuromuscular control strategy of the upper limb during grasping with/out tapping executed with a smartphone by evaluating muscle-activation patterns of the upper limb during different movement conditions (MCOND). There was a change in muscle activity for MCOND and segments. We concluded that our neuromuscular system generates the motor strategy that would allow smartphone manipulation involving grasping and tapping while maintaining MCOND by generating continuous and distinct multi-muscle activation patterns in the upper limb muscles.

In the second study (chapter 3), we examined the muscle activity of the upper limb when the smartphone was manipulated at two arm heights: shoulder and abdomen to understand the influence of the arm height on the neuromuscular control strategy of the upper limb. Some muscles showed a significant effect for ABD, while some muscle showed a significant effect for SHD. We concluded that the motor control strategy was influenced by the arm height as there were changes in the shoulder and elbow joint angles along with the muscular activity of the upper limb. Further, shoulder position helped in holding the head upright while abdomen reduced the moment arm and moment and ultimately, muscle loading compared to the shoulder.

Overall, our neuromuscular system generates motor command by activating a multi-muscle activation pattern in the upper limb, which would be dependent upon the task demands

such as grasping with/out tapping, MCOND, and arm heights. Similarly, our neuromuscular system does not appear to increase muscle activation when there is a combined effect of MCOND and arm heights. Instead, it utilizes a simple control strategy that would select an appropriate muscle and activate them based on the levels of MCOND and arm heights.

CHAPTER 1. INTRODUCTION

Early history shows that humans have used their hands and arms for hunting and self-protection from their adversaries. For example, handheld tools like bow and arrow, choppers, axes, hammers, knives, etc. were ubiquitous in the Stone Age period (Hogenboom 2015). Thus, manipulation with hands and fingers was a vital part of a life long before human civilization morphed into today's modern technology-based society. Remodeling of the hand structures and associated musculature likely occurred to improve our hand and finger motions, making them more dexterous than any of our predecessors (Weiss and Jeannerod 1998; Gordon 2001; Young 2003; de Freitas et al. 2008; Liu et al. 2016). Over the years, human interaction with objects has expanded with the advances in technology, resulting in increasingly complex interactions requiring more coordination and control. This prompted researchers to examine the structure and function of the human hand and control strategies used to perform the dexterous hand-object interaction.

The human hand is considered as one of the most complex segments (structures) of the human body because of its neurological and biomechanical constraints (Hager-Ross and Schieber 2000; Mason et al. 2001; Schieber and Santello 2004). These two constraints allow the hand to possess several degrees of freedom (DOF) for motion, i.e., flexibility and adaptability to move hands in different ways and perform a wide range of daily tasks comfortably (Weiss and Jeannerod 1998; Huang 2012; Santello et al. 2013). However, these DOFs due to limb joints, connective tissues, etc., have been viewed as a potential problem for central nervous system (CNS) control. The CNS has to control a large number of DOF simultaneously, which could become complicated and challenging, also known as redundancy or DOF problem suggested by Bernstein in 1967 (Bernsteĭn 1967). The CNS also has to control these DOFs while monitoring

the sensory inputs coming from tactile, visual, and auditory channels (Weiss and Jeannerod 1998; Flanagan et al. 2006; Johansson and Flanagan 2009). Once these mechanical and sensory events have been registered, the CNS solves the given motor problem by generating appropriate neural motor commands for the motor neurons of the muscle group of the involved effectors. In this way, the CNS smartly utilizes available DOFs for movements to reduce its computation complexity (De Luca and Mambrito 1987; Johnston et al. 2004; Semmler et al. 2004; Winges and Santello 2004; Winges et al. 2008). Additionally, the sensorimotor system is continuously involved in estimating and predicting sensory consequences that arise from these motor commands that helped to reach the goal of the given task (Flanagan et al. 2006). There have been many attempts to understand the central neuromotor commands and pathways used to generate a synergistic controlling mechanism (strategy) for the hand and arm to execute a wide range of motor tasks like object manipulation.

Humans are unique among primates because of their increased capacity to move their fingers and thumb independently (individually) (Schieber 1991; Schieber 1995; Lang and Schieber 2004). Coordinated movements among the digits could result in synergistically co-varying the DOFs from the joints, connective tissues, and neural connections (Nakamura et al. 1998). The resulting repertoire of possible movements is used to define different grasping patterns, which have resulted in several grasping taxonomies (Napier 1956; Feix et al. 2016). For example, grasping taxonomies have been based upon the number of fingers being used (Napier 1956) or the nature of the contact made by the hand with the given objects (Kamakura et al. 1980). In the past, researchers examined finger individuation and covariation across the joints to describe synergies of hand postures during object manipulation (Santello et al. 1998; Santello and Soechting 1998; Mason et al. 2001; Todorov and Ghahramani 2004), unconstrained haptic

exploration (Thakur et al. 2008), typing (Flanders and Soechting 1992; Soechting and Flanders 1992; Soechting and Flanders 1997; Baker et al. 2007), piano playing (Bejjani et al. 1989; Aoki et al. 2005; Furuya et al. 2011), finger-spelling (Jerde et al. 2003a; Jerde et al. 2003b; Weiss and Flanders 2004), and finger tapping tasks (Kuo et al. 2006; Dennerlein et al. 2007).

Synergistic joint control has also been observed in the proximal and distal segments of the upper limb as well. There is inter-joint coordination between the proximal (arm) and distal (hand/fingers and wrist) segments of the upper limb, supporting an idea of unique coupling between these segments (Paulignan et al. 1990; Paulignan et al. 1991a; Paulignan et al. 1991b). Such coupling action helps us to perform a wide range of functional motor tasks for daily living, such as drinking water (Safaee-Rad et al. 1990; Alt Murphy et al. 2006), typing (Flanders and Soechting 1992; Soechting and Flanders 1992), and playing the piano (Aoki et al. 2005). However, such inter-joint coordination could be impaired or altered among individuals suffering from neurological disorders such as stroke (Roh et al. 2013) and hemiplegia (Kim et al. 2014a).

Researchers were also intrigued to understand the significance of the muscles controlling the proximal and distal segments. Hence, they started examining the muscular activation of the upper limb to understand the role of the CNS in executing different motor tasks like grasping, tapping, and so on. These skills were assisted by the motor system that would send out the necessary commands to the motor neurons of the muscles of the involved limb, resulting synergistic activation of the muscle pairs to maintain specific arm postures in the proximal and distal segments while simultaneously carrying out multi-digit grasping tasks (Maier and Hepp-Reymond 1995; Winges and Santello 2004; Winges et al. 2007; Martelloni et al. 2009; Vermillion et al. 2015). For example, researchers investigated the role of two thumb muscles involving thumb to secure objects in hand by examining tasks like pinching in both stable and

unstable conditions. They found that these thumb tip forces produced during the motor task were stabilized by the Abductor Pollicis Brevis (APB) and Extensor Pollicis Longus (EPL), explaining the role of these two muscles in generating the thumb-tip force. Likewise, Kuo et al. (2006) found the onset of both intrinsic (FDI) and extrinsic (ED) muscle activation such that these muscle activations begin with the downward motion of the index finger involved in tapping, which resulted in coactivation of these two muscles. Others suggested that muscular activity was the smallest for the neutral wrist position compared to the other wrist positions recommending this position while playing the piano to reduce musculoskeletal injuries (Oikawa et al. 2011). Further, sequential finger movements involved in playing piano implemented by the pianists used a neuromuscular co-articulation strategy to press keys rather than producing a fixed amount of muscular burst pattern in a sequential manner (Winges et al. 2013). Such examination of muscle activation patterns helps us to understand that there is a neuromuscular strategy behind the control and coordination of the upper limb’s facilitated by the motor system during motor behavior.

Besides analyzing the motion and the muscle activity of the upper limb, researchers have also focused on examining the forces applied by the fingers onto the object while accomplishing different manipulative tasks. Using a force transducer on the object, researchers have examined the manipulative forces and moment generated by each digit, and its joints during various activities such as opening and closing a water bottle or jam jar with two hands (Fowler and Nicol 1999a; Fowler and Nicol 1999b). Examination of such manipulative forces applied to the objects using the fingertips pad facilitated by the connective tissues and joints also helped to define the characteristics of normally functioning hands (Chao et al. 1976). Also, these manipulative forces have been useful in describing the role of the neural system as it helps in modulating the

fingertip forces during object manipulation tasks (Flanagan et al. 1999; Johnston et al. 2009). Further, these applied finger forces were divided into two types: grip (normal to contact surface) and load (tangential to contact surface) forces. Grip and load forces during gripping were temporally coupled, such that grip forces were higher than load forces to prevent slippage and provide stability for object manipulation (Westling and Johansson 1984; Johansson and Westling 1984; de Freitas et al. 2008). The total force applied to the object is shared among the fingers in a specific manner, solved by the CNS (Latash et al. 1998; Li and Yue 2002). These manipulative forces were also influenced by the arm movement (involving vertical and horizontal point-to-point movement) while transporting an object (Flanagan et al. 1993). Such coordinated modulation of forces during object manipulation depicts the versatility of the CNS, which could be compromised by neurological movement disorders (Ingvarsson et al. 1997; Nowak and Hermsdorfer 2002a; Nowak and Hermsdorfer 2002b; Nowak et al. 2002; Nowak and Hermsdorfer 2004). These manipulative forces exhibited by the distal segments during grasping are supported by the proximal segment, suggesting the reaching and grasping task involving proximal and distal segments of the upper limb is coordinated due to the complex neural coupling between these two segments and are involved in activating the associated muscles temporally to execute the gripping task successfully (Paulignan et al. 1990; Vermillion et al. 2015).

Besides tasks used for stationary object manipulation such as typing on a keyboard or playing piano, humans have been involved in other types of object manipulation tasks such as carrying and transporting a grocery bag or a coffee mug with our hand(s). Such object manipulation tasks involved both upper and lower limb movements have been a regular activity of our daily living. However, controlling of both upper and lower limbs involved in two different

motor tasks simultaneously could require a complex mechanism formulated by our neuromotor system. For example, Georgopoulos and Grillner suggested that locomotion and reaching tasks are intimately connected to motor activities when transporting an object. Both motor skills require the motor cortex and its corticospinal neural connections to actively and passively position the upper and lower limbs while executing the tasks together (Georgopoulos and Grillner 1989). Moreover, our motor system finds a systematic way to organize the upper and lower limbs simultaneously, which would superimpose prehensile movements involving reaching and grasping in the arm swing of walking without interfering/destabilizing gait action (Carnahan et al. 1996). What happens to upper limb motion and its control when holding an object while the lower limbs are involved in locomotion? It is essential to understand the control mechanism implemented by the motor system, as walking creates a perturbation to the upper limb. This perturbation could result in an adverse effect on the stability of the arm and hand when holding an object. Mizrahi and colleagues (2011, 2017) found that participants can vary their mechanical impedance (stiffness and damping) individually, suggesting that humans are capable of regulating their impedance without restricting the joints while executing a task like stabilizing a cup filled with liquid during walking (Roth et al. 2011; Mizrahi et al. 2017). This led them to suggest that the human body optimizes a flexible control mechanism that would reduce the hand vibration (jerk) and maintain a constant position of an object held in hand during walking. This flexible control mechanism also dampens hand vibration depending upon the task demands (external workspace) and the internal body state (Togo et al. 2012; Togo et al. 2014; Togo et al. 2015).

In other cases, the human motor control system anticipatorily couples the grip and inertial forces during object transport and dampens the vertical movement of the object relative to the

body by lowering the inertial force. This helps to lower the grip force applied onto the object to improve overall inter-segmental coordination of the trunk and arm (Gysin et al. 2003; Diermayr et al. 2008). Here the CNS dampens the arm motions by increasing the muscle activity and subsequently the joint stiffness by utilizing the available DOFs (degrees of freedom) of the involved limb as soon as it detects walking, resulting in perturbation of the arm and dynamics of the object held by the arm (Kwan et al. 1979; Lacquaniti and Soechting 1984; Milner and Cloutier 1995; Milner and Cloutier 1998; Gysin et al. 2003). This increase in muscle co-contraction helps to increase joint impedance and provide greater stability of the limb when it is faced with perturbing forces or dynamic environments (Gribble et al. 2003). However, such anticipatory control of grip-inertial forces applied onto the objects is impaired among the population group with Parkinson’s disease, as they generate higher grip force and lower dampening effect onto the held objects during walking (Albert et al. 2010).

In short, we, as a human, interact with different types of objects repetitively while maintaining different body position. Moreover, our neuromuscular system plays an important role in the efficient execution of an object manipulation task. Whether the hand-object interaction involves the upper limb only or it involves both the upper and lower limbs during object transport, the human motor system is continuously involved in sensorimotor transformation related to hand and/or arm control by yielding a control strategy to maintain a steady position of the manipulating limb regardless of the nature of the task or environmental constraints. For example, control strategy related to the postural and muscular synergies have helped to produce systematic hand/arm motion, generating muscle activity, and finger forces to do different motor skills such as typing (Flanders and Soechting 1992; Soechting and Flanders 1997), and prehension (Santello et al. 1998; Santello and Soechting 1998; Mason et al. 2001).

However, there have not been many studies that have tried to understand the role of the neuromuscular system and its control strategy for cellphones or smartphones during standing or walking or maintaining different arm height for selfies.

Smartphones have also become a ubiquitous tool in our lives. We have been controlling our upper limb movement to interact with smartphones using our hand(s) while simultaneously maintaining various body positions such as standing and walking. Hand-smartphone manipulation is a complex example of object manipulation simply because its manipulation involves multiple layers of compounded motor actions. Users have to hold the device using their palm and fingers firmly. Once held securely, they either actively move their thumb to make several keystrokes (keypresses) for executing cellular tasks like texting or passively minimize the thumb motions for performing other cellular tasks like reading and internet browsing. These keystrokes made by the thumb during active or passive tapping could be divided into three key moments, similar to the finger movement involved in a computer typing. During thumb tapping (keystroke), humans move their thumb in the direction of the target key to be pressed, then move down to press the key resulting thumb tip compression (impact) and release the key by lifting the thumb and return to the position for next keystroke (Dennerlein et al. 1998). While this is happening, in parallel, its users are required to stabilize (flex) their upper arm and forearm at a certain angle, lock their wrist, and shape their hand to hold the device. This action would restrict the upper limb in a specific position, allowing its users to keep the device within viewing distance and execute different cellular tasks using their thumb. This arm stabilization is also required to be maintained when individuals are standing or walking and do not have any supporting surface underneath the arm, as in the case of sitting. The flexed arm height allows people to overcome the gravitational and inertial forces acting upon the unsupported arm and

hand that could be generated during standing and walking conditions (Togo et al. 2012). Accomplishing these motor actions in series and parallel could pose a unique challenge for the neuromuscular system of the human body especially the hand and arm as they have to continuously transform the sensorimotor information and facilitate a control strategy that would help in producing different hand and arm motions, necessary muscular activity pattern, and finger forces. Hence, smartphone manipulation is similar to any other object manipulation involving multi-digit hand and arm control. However, there is some distinctness between this manipulation and others. First, the thumb and the four fingers are not used for grasping purposes; instead, the thumb is used for pressing the device's keys while the other four digits along with the palm and thenar eminence are involved in supporting (or holding) the device. Secondly, the arm is stabilized at certain angles, which stabilizes the dynamics of the smartphone held within the hand and helped to keep the device within a viewing distance when it is required to execute a cellular task. Hence it becomes essential to understand these neuromuscular strategies formulated by the CNS for smartphone manipulation across different task constraints.

Past studies related to cell/smartphones have mainly focussed upon recording and evaluating the thumb kinematics (Jonsson et al. 2007; Ong 2009; Sakai and Shimawaki 2010) along with the thumb peak forces during cellphone tapping (Ong 2009). Other studies have examined the muscular activation of the hand, arm, shoulder, and neck areas while executing cellular tasks like texting, talking, web-browsing or video watching and maintaining different body postures like sitting, and standing and texting techniques (Gustafsson et al. 2010; Gustafsson et al. 2011; Lee et al. 2015). Past studies have also evaluated the muscular activity of the upper limb during different types of cellphone holding technique including one hand versus two hands, cellphone orientation: portrait versus landscape (Hong et al. 2013; Kim et al. 2014b)

and at different heights (Ko et al. 2016). Moreover, with the advent of smartphones, cellphones with tactile keypad have been replaced by touch screen smartphones, which have a virtual keyboard. These devices have now allowed touchscreen text entry methods, shape-writing recognition (e.g., swype), and handwriting recognition besides thumb tapping with the help of onscreen Qwerty keyboard input (Smith and Chaparro 2015). Lai and Zhang (2014) compared tapping and gesture-based input entry (or shape-writing recognition) methods like swipe/swype and have suggested that swipe/swype is significantly faster and more accurate than tapping; thus, this method is becoming more popular than tapping.

In summary, past studies related to object manipulation did not include neuromotor control strategies (instigated by our neuromotor system) as related to specific types of object and its manipulation, such as smartphone manipulation involving grasping with/out tapping while simultaneously involving different body postures. Studies related to cell/smartphone, moreover, did not consider how we are stabilizing our upper limb posture to execute any tasks (grasping with/out tapping) on the smartphone across different body positions (during standing and walking). Thus, it is imperative to understand such complex hand-smartphone manipulation as it could involve neural control strategy(es) generated by the neuromotor system to control fine motor control of the digits for holding and tapping of the device while in maintaining the stability of the arm and the whole body. Although there is a basic understanding of arm control and its association with body motion, how these specific multi-layered motor tasks are carried out by the CNS for the humans during smartphone manipulation is still unknown. Examination of the upper limb during smartphone manipulation is important, especially in this day and age, because several studies have suggested that we are spending several hours each day performing various cellphone tasks. These extended hours on such devices could put us at risk for

developing overuse injuries. Moreover, with the advancement in technology, the smartphone is now becoming more than a phone; as a result, we are using it everywhere for multiple purposes.

This project aims to determine what motor control strategies in terms of muscular pattern that are used to control and coordinate each segment of the upper limb during these complex hand-object interactions for different realistic interaction conditions such as different arm height and interaction with inertial forces such as those generated during level walking and compared that to the standing. Also, this examination of the muscular activation of the upper limb during cellphone manipulation could provide more insight into the neurophysiology of the hand and arm that are involved in smartphone manipulation. This knowledge could be useful in the treatment of those who have musculoskeletal disorders of the hands and arm due to its excess usage over time. Such an understanding of thumb movement may also aid in designing a more efficient virtual keypad, which can reduce the muscular impact/loading while making those taps. Therefore, the general purpose of this project is to examine the muscular activation pattern of the upper limb during smartphone manipulation involving grasping and tapping, different movement conditions such as standing and walking, and arm heights such as shoulder and abdomen levels.

CHAPTER 2. EFFECT OF TASK AND MOVEMENT CONDITION: STUDY 1

INTRODUCTION

There have been many studies that have tried to understand the hand and arm involving different objects commonly used in our daily living. The goal of those studies was to understand the movement patterns and muscle activity using kinematics and electromyography measurements. Using these biomechanical measurements, past studies have helped us to understand the neuromuscular strategies related to the hand-object manipulation required for the upper limb. Past studies related to cell/smartphones mainly examined the thumb kinematics (Jonsson et al. 2007; Ong 2009; Sakai and Shimawaki 2010), thumb peak forces during tapping (Ong 2009) and the muscular activity of the upper limb while executing tasks like texting, talking, web-browsing or video watching and maintaining different body postures like sitting, and standing and texting techniques (Gustafsson et al. 2010; Gustafsson et al. 2011; Lee et al. 2015). However, there are not many studies that have compared the multi-muscle activation patterns of the upper limb during this multi-layered hand-smartphone interaction by considering muscle activity during different segment of the trials involving grasping with/out tapping and MCOND. Similarly, those studies did not describe the neuromuscular strategy behind hand-smartphone interaction. Thus, the primary purpose of this study was to compare and evaluate multi-muscle activation patterns associated with the upper limb during thumb tapping, before and after tapping for different movement conditions: standing and walking to understand the neuromuscular control (strategy) formulated for the upper limb involved in smartphone manipulation and during movement conditions. We first hypothesized that arm and hand muscle activity would increase before thumb tapping and maintain an increased level until thumb returns to start (‘Home’ button) position. The rationale behind this hypothesis was that the increased

muscle activity in hand and arm would be used to stabilize arm and hand position needed to hold the device firmly before and during tapping. This increase in muscular activity will occur before tapping as an anticipatory activation, will increase the muscle activity level during the task and later will return to the original baseline level once the thumb has completed the tapping task. Our second hypothesis was that increased muscle activity of arm and hand muscles would be modulated with the gait cycle due to inertial forces during walking. The rationale behind this hypothesis was that the grip forces are modulated with respect to arm movements, thus coordinated modulation in the arm and hand muscle activity is expected. As walking speed increases, the inertial forces that need to be countered will increase, requiring increased muscle activity.

METHODS

Participants

Twenty-four students (8 males and 16 females) age range from 19 to 22 years (*M*=20.96, *SD*=0.95), and height range from 1.57 to 1.85 m (*M*=1.68, *SD*=0.10) were recruited from Louisiana State University (LSU) with no self-reported neuromuscular, or orthopedic history. Participants were tested for Finkelstein and Phalen's test to confirm whether they have any irritation or pain at/around the base of the thumb and in their carpal tunnel and medial nerve in the wrist due to excessive usage of the smartphones respectively. They showed a negative result for the Finkelstein and Phalen's test (Appendix C). They also self-reported either normal or corrected to normal vision (Appendix D). Based on their online questionnaire response, participants had been using their smartphones for a minimum of two years to more than ten years (Appendix H). Edinburgh handedness inventory test (Appendix I) showed that 21 participants were right-handed (R>+40), two were ambidextrous ($-40 \le R \le +40$), and one was left-handed (R

< -40) (see Appendix D for the full score). The left-handed participant used her right hand for smartphone manipulation for several years.

Hand and arm anthropometry data of each participant were measured, as shown in figure 2.1 before the markers and electrodes were placed on the body. Past studies have suggested that hand anthropometry could influence an individual's ability to type and grip a handheld device like smartphones (Balakrishnan and Yeow 2008a; Balakrishnan and Yeow 2008b; Pereira et al. 2013). Table 2.1 summarized the average participants' hand and arm anthropometry data (Appendix E for each participant's demographics, hand, and arm anthropometric data and handedness test details). Participants signed the consent form approved by the LSU Institutional Review Board (IRB) (Appendix A). They were given extra-credit for their participation in one of their Kinesiology classes at the University. The experimental session lasted three hours.

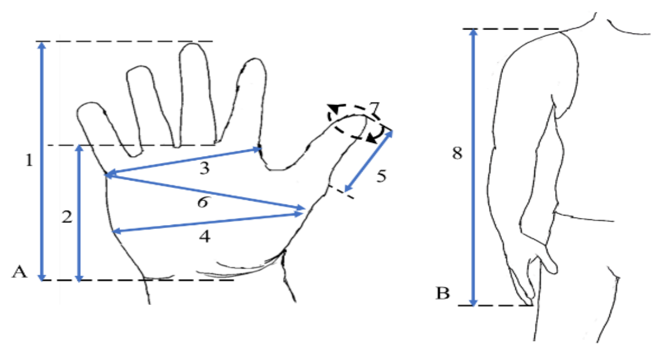


Figure 2.1. Hand (A) and arm (B) measurements

Table 2.1. Anthropometric data for hand and arm in centimeters

#	Dimension	Mean (SD)	#	Dimension	Mean (SD)
1	Hand length	18.1(1.1)	5	Thumb length	6(0.5)
2	Palm length	10.6(0.7)	6	Palm breadth	10.8(1.4)
3	Distal handbreadth	8.2(0.7)	7	Thumb circumference	5.6(0.4)
4	Maximum handbreadth	10(1.3)	8	Arm Length	71.5(4.3)

Surface electromyography (sEMG) data collection apparatus

A 16 channel EMG system (MA 400-28) and two types of EMG preamplifiers, MA-411 and MA-422 (Motion Lab System, Baton Rouge, LA), were used to record the muscle activity of the fourteen muscles of the upper limb. Muscle activities were collected from the following muscles of the upper limb: hand (First Dorsal Interosseous (FDI), Abductor Pollicis Brevis (APB), Abductor Digiti Minimi (ADM)), forearm (Flexor Carpi Radialis (FCR), Extensor Carpi Ulnaris (ECU), Extensor Pollicis Longus (EPL), Extensor Digitorum (ED)), upper arm (Biceps Brachii (BIC), Triceps Brachii (TRI)), shoulder (Anterior Deltoid (ADEL), Medial Deltoid (MDEL), Posterior Deltoid (PDEL)) and neck region (Right Trapezius (RTRAP), Left Trapezius (LTRAP)). For hand muscles, two snap leads of EMG preamplifier MA-422 were attached with a pair of disposable GS26 Pre-Gelled Disposable sEMG Electrodes (Bio-Medical Instruments, MI). In contrast, for the upper arm, shoulder, and neck region, two snap leads of EMG preamplifier MA-422 were attached with a pair of Neuroplus EMG disposable medical gel electrode (A10040-5, 22.225mm) (Vermed, A Nissha Company, Buffalo, NY). Similarly, EMG preamplifier MA-411 has two 12-mm medical-grade stainless-steel disk electrodes, and it does not require any electrode cream or gel.

EMG signals were recorded at 2400 Hz. Each target area of a muscle was palpated, shaved if needed, abraded, and cleaned using alcohol and cotton to remove oil/lotion and callused skin before the electrode placement. Electrode placement areas were determined using Surface EMG Non-Invasive Assessment of Muscles (SENIAM) guidelines (Hermens et al. 2000) or a book titled as Anatomical Guide for the Electromyographer The Limbs and Trunk (Perotto 2011) (Appendix J). Once the electrode was placed on the individual muscle, the end of the EMG preamplifier was plugged into the appropriate channel of the 16 channel EMG system (MA

400-28). Participants made a specific movement to activate that muscle (Appendix J). Based on the muscle activation monitored on the computer screen, the placement of the electrode was verified. The electrode was then secured with either Cover-Roll™ Stretch Bandage - 2", or Transpore™ Tape - 1" (hypo-allergenic surgical tape), or self-stick stretchable compression tape (2 x 1.5 x 1 inch, Cramer Eco-Flex Self-Stick Stretch Tape) to prevent movement of the electrodes and preamplifiers. Usages of a particular type of the tape or bandage were dependent upon the muscle area. However, the electrode was removed, and the new electrode placement area was identified, and the previous steps - cleaning, placing, and securing were repeated if the EMG signal was poor due to improper placement of the electrode. This process of muscle palpating, shaving, abrading, and cleaning with alcohol and usage of appropriate EMG preamplifiers with/out electrodes were repeated for all the muscles and connected to their respective channels of the EMG system.

Kinematic data collection apparatus

Participant's upper and lower body movements, along with the smartphone movement, were captured by the Oqus-300 motion capture system (Qualisys, Gothenburg, Sweden). Kinematic data were collected at 120 Hz. There were eight cameras, which were spread around the split-belt treadmill (Bertec Instrumented Treadmills, 1.75 x 0.5 (m) each, and approx. 0.4 m above the ground) on which participants performed all trials. Thirty-four passive retroreflective hemispheric markers (of 9.5 mm and 25.4 mm in diameter) were placed on the following landmarks as shown in figure 2.2 (A) and 2.2 (B) for the kinematic data recordings: temples, the dorsal side of the head, Spinous process of the 7th cervical vertebrae, acromia, lateral humerous epicondyles, styloid processes of radius and ulnar, greater trochanters, medial ½ of the right femur, lateral femoral condyles, lateral malleoli, calcanei, distal phalange, interphalangeal,

metacarpophalangeal and carpometacarpal of the thumb, heads of metacarpals and bases of the second and the fifth digits (Lee and Jung 2014), the dorsal side of the radius and ulnar of the forearm and the edges of the device (Appendix K). Using double-sided tape, these markers were placed on the skin, except the markers of the feet (which were placed on the participant's shoes outer sole) and the device (which were placed on the edges of the device as shown on figure 2.3). Before the actual trial recording began, visibility for all the 34 markers was verified. Figure 2.2 (A), 2.2 (B), and 2.3 show the placement of the markers on the human body, and the smartphone device.

Handheld mobile device

An LG Leon smartphone device designed and manufactured by LG electronics was used as a handheld mobile device for this study (Figure 2.3). Its dimension was 5.11" (H) x 2.55" (W) x 0.43" (D). had a screen size of 4.5 " full wide VGA display with a screen resolution of 854 x 480 pixels. Its total weight was 120 gm (4.89 oz.).

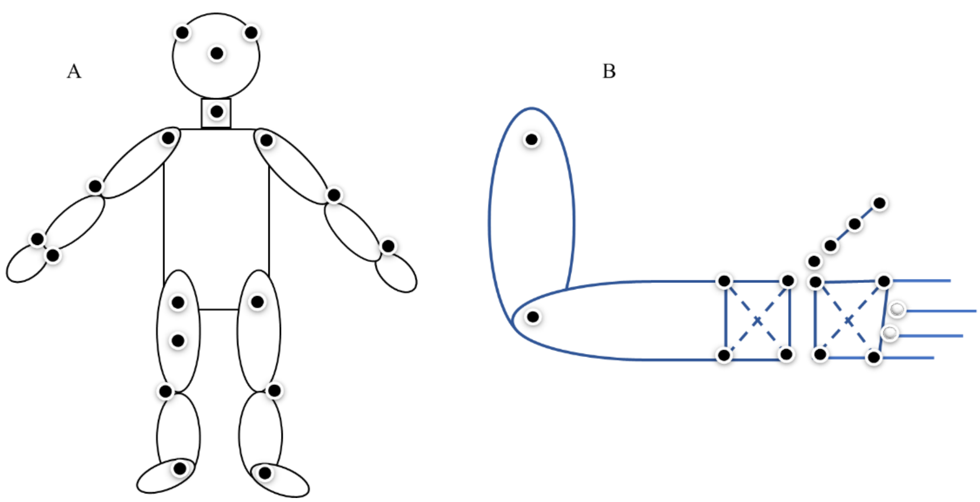


Figure 2.2. A human model with passive markers (A) and Marker placed on the upper limb (B)

Figure 2.3. Smartphone with three passive markers and showing Home button, target letters (keys) colored in red and yellow

Experimental Conditions: Grasping with/out tapping task

There were five tasks executed in each block summarized in table 2.2. The first task was defined as a Grasping and no-tap, which was used as a static reference for EMG. The other four tasks were defined as Grasping and tapping tasks that included two single and two multi-tap tasks. Participants were instructed to type as naturally as possible at their comfortable typing speed as they would do in their daily lives. They were also instructed to type accurately. In case if they made an error, they would inform the primary investigator (PI) and redo the trial. Further, they would ignore the letter case while typing and were not allowed to use the automatic word completion function.

Participants were verbally and visually reminded of the task to be completed and through a computer monitor placed in front of and at a distance of 52" and the height of 45". Participants rested their thumb on the 'Home' button of the device ('LG' logo), as shown in figure 2.3, before and after each task. They began the given task when they heard the 'Go' signal from the PI, and they responded loudly 'Done' once the task was over, and the recording was then stopped. All tasks were recorded in the note-taker application of the given device.

For the Grasping task, participants were instructed to rest their thumb at ‘Home’ as shown in figure 2.4 (A) or 2.5 (B) while kinematics and EMG data were recorded for a few seconds (approximately 5-6 seconds). They were instructed to look at the screen of the smartphone device by focusing on the letter ‘G’ of the keypad. Once the recording was over, they removed their thumb from the ‘Home’ position and relaxed.

Prior to the start of Grasping and tapping tasks, participants rested their thumb at ‘Home’ as shown in figure 2.4 (A) or 2.5 (B). In a single-tap task, each participant tapped five single target letters such that each target letter was tapped in between the ‘Home’ button. For example, participant’s tapping sequence would be: H▸Q▸H▸G▸H▸M▸H▸G▸H▸Q▸H where H is the ‘Home’ button of the device, and Q, G, M are the target letters (keys) typed in between the Home button taps. They repeated this step for other letters set shown in table 2.2.

In a multi-tap task, trials began and ended at the ‘Home’ button while five letters were tapped consecutively in between. For example, H ▸QGMGQ▸ H, where H is the ‘Home’ of the device, touched at the start and end of a trial, and in between, the five letters: Q G M G Q were tapped consecutively. Both single and multi-tap tasks required participants to tap target letters diagonally positioned either from Left to Right (LR) (NW, NorthWest ↔ SE, SouthEast) or Right to Left (RL) (NE, NorthEast ↔ SW, SouthWest) direction. These target letters are highlighted on the device shown in figure 2.3.

Table 2.2. Smartphone manipulation Task

Nature	**Task**	**Task direction**	**Executed task**	**Trials per block**
Grasping	No-tap		Thumb rested at ‘H’	2
Grasping and tapping	Single tap	LR (NW ↔ SE)	H▸Q▸H▸G▸H▸M▸H▸G▸H▸Q▸H	1
		RL (NE ↔ SW)	H▸P▸H▸G▸H▸Z▸H▸G▸H▸P▸H	1
	Multi-tap	LR (NW ↔ SE)	H▸QGMGQ▸H	1
		RL (NE ↔ SW)	H▸PGZGP▸H	1

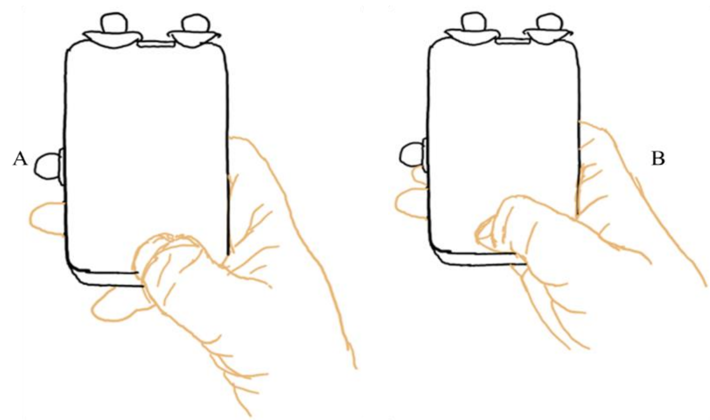


Figure 2.4. A. Thumb resting on the Home button and placement of the little finger at the bottom of the device. B. Thumb resting on the Home button and placement of the little finger on the side of the device

Experimental Conditions: Movement condition (MCOND)

The five manipulation tasks were performed under different movement conditions (MCOND) that included standing and walking at different percentages of comfortable walking speed with the device (CWSD) on the split-belt treadmill. During standing (W0), participants stood with feet shoulder-width apart flat on the treadmill and maintained this position while executing the manipulation tasks. For safety purposes, there were handrails and a spotter standing nearby. Before recording began, participants were allowed to tap on the device while standing or walking to help them to acclimatize to the MCOND for the trial.

Each participant's CWSD was defined individually. First, participants stood on the treadmill, and the PI set a comfortable walking pace on the treadmill. By holding the device in a comfortable position and walking simultaneously, they were instructed to type about themselves on the device. They were asked to imagine their walking speed while they interact with the device. Once the speed has matched to their real-life walking speed while interacting with the device, the treadmill was stopped, and this speed was defined as CWSD (Ng et al. 2014) and corresponded to 100% CWSD (W100). This speed was used to calculate the slow and fast

walking, where slow was 80% of CWSD (W80), and fast was 120% of CWSD (W120) (Lin et al. 2005). The average CWSD for these twenty-four participants ranged between 1.80 and 3.60 (*M*=2.55, *SD*=0.43 kmph). Participants' comfortable walking speed without the device (CWS) was also recorded to compare the two gait cycles with/out the device. They were asked to imagine their normal comfortable walking speed when they walk to their school or from class to class. The average comfortable walking speed without the device for these twenty-four participants increased and ranged between 1.84 and 3.28 (*M*=2.73, *SD*=0.37 kmph).

Dependent Variables

The dependent variables analyzed were integrated EMG/time (iEMG/time) and the range of amplitude modulation index. The iEMG/time represented the amount of activity (or the effort) in each muscle, and in this study, iEMG/time was measured by finding the Start and End points of a trial. Here the Start point was defined as the point when the thumb lifted (moved) away from the 'Home' button to type the instructed keys once the participants heard the 'Go' cue. This movement was followed by the thumb movement to press the instructed keys. Figure 2.6 (A) shows the thumb movement as represented by a black down and orange up arrows. While the End point of the task in each trial was defined as the point when the participant rested his/her thumb completely by touching on to the 'Home' button once s/he finished entering the target letters. In this study, iEMG/time was calculated for the Pre-start, Post-end, and during tapping (between Start-End points). The range of amplitude modulation index (AMI) for all the fourteen muscles between Start-End points was calculated for all the twenty conditions. This range of AMI value was used to assess the variation in muscular activity between conditions involving a grasping with/out tapping and movement condition (MCOND) with that of the baseline muscular activity involving grasping and standing.

General Procedure

Once the participant arrived in the lab, s/he was explained about the purpose and procedure of the study. They signed the consent form, fill out the questionnaire, and the Edinburgh handedness inventory test. Their hand and arm were measured and followed by the Finkelstein test (Thumb), and Phalen's test (Wrist). Participants' smartphone grasping patterns were also asked to find out whether they hold their device, either one of the positions shown in figure 2.4. Afterward, they were applied with the 14 EMG electrodes and 31 markers. Before the recording for the study started, each participant's comfortable walking speed with/out the device was determined. Participants then practiced the instructed tapping task on the given device while simultaneously stand and walked on the treadmill. In total, there were 120 trials, divided into 20 blocks. Each block was randomly defined as standing or walking, such that each block had six randomly arranged tapping and no-tapping tasks. This randomization prevented any learning and anticipatory effect exhibited by the participants. They were given several breaks throughout the experiment to prevent fatigue.

Data Analysis

Thirty-four markers were labeled offline using Qualisys's QTM software. Using this software, kinematic data of the 34 markers and analog EMG data of the 14 muscles were saved as the MAT files. These MAT files were analyzed using several customized MATLAB scripts (R2018b) to examine the kinematics and EMG data and understand the neuromotor control strategy formulated by our motor system for the hand and arm segments while doing different tasks and maintaining a different level of mobility on the treadmill. Out of 47 participants, 24 participants produced usable data, while 23 participants' data were excluded because either the

participant's markers were not identified by the software during offline analyses or EMG signals of the muscles had significant movement artifacts and/or did not record correctly.

Kinematic data were filtered offline using a zero-lag, fourth-order Butterworth filter with a 10 Hz cutoff frequency, which was later resampled to 1000 Hz. Thumb local coordinates were computed relative to the smartphone using the distal thumb marker along with three smartphone markers. Raw EMG signals were filtered offline by first with a 30 Hz high-pass, zero-lag, fourth-order Butterworth filter to remove low-frequency noise. Next, these filtered EMG signals were detrended (to remove the DC trend) and rectified. Finally, the signal was with a 20 Hz low-pass, zero-lag, fourth-order Butterworth filter to obtain a smoothed EMG signal, which was down-sampled to 1000 Hz similar to the kinematic data. Figure 2.5 shows the thumb local kinematics relative to the surface of the smartphone, along with filtered and rectified EMG of hand and forearm muscles of a participant during the no-tap task (A) and multi-tap task as 'PGZGP' (B) during standing. Reference values were created and saved using a MATLAB script for each tapping task and movement condition performed during a trial (Appendix M).

The Start and End points of a trial from the thumb local kinematics, the number of the thumb keypresses on the touchscreen for a given task trial, and delete any extra erroneous taps were computed. Figure 2.6 (A) shows an output obtained from a script showing thumb local kinematics with Start and End points along with the five thumb-key presses. The Start point was defined through an automated process by defining a threshold value. It is assumed that if the thumb local kinematics' value was greater than the threshold value, then it meant the thumb had moved away from the 'Home' position. The threshold value was thus defined as the sum of the average of thumb local points for the first 500 points and 0.5 mm. Since the thumb moved in the z-axis (direction), the first point was identified to find that the z coordinate (of the thumb local

kinematics) was greater than the threshold value. This point was later added back to the skipped points from the Start, and the final value (point) was identified as the Start point of the thumb moving away from the 'Home' button. When this automated script was not able to identify the exact Start point of a trial, the Start point was thus identified manually using the MATLAB software.

Similarly, the End point on the local thumb kinematics was defined basically in two ways. Using a script, the automated process started to find the End point from the last point, such that the End point was conditioned to be greater than the last point but one less than the last point. In case, if this process failed to identify the exact End point of the thumb, the End point was identified manually by finding the lowest valley area of the thumb kinematics using the data tips pointer of the MATLAB. Identification of the number of the thumb keypresses (strikes) on the device during a given task trial and deletion of any extra erroneous thumb keypresses (strikes) by computing the number of the zero-crossing points. Here, the zero-crossing points represented the number of times the thumb moving downward to the upward direction, making contact (touch) to the keys of the device. Figure 2.6 (B) showed that the five blue asterisks (*) represented the five zero-crossing points, and they represented five thumb keypresses. The five red valleys represented these five thumbs keypresses. Valleys in the thumb local kinematics representing contact with the device surface were identified around the zero-crossing with a threshold of ±2mm/s, as shown by the dotted lines in figure 2.6 (B).

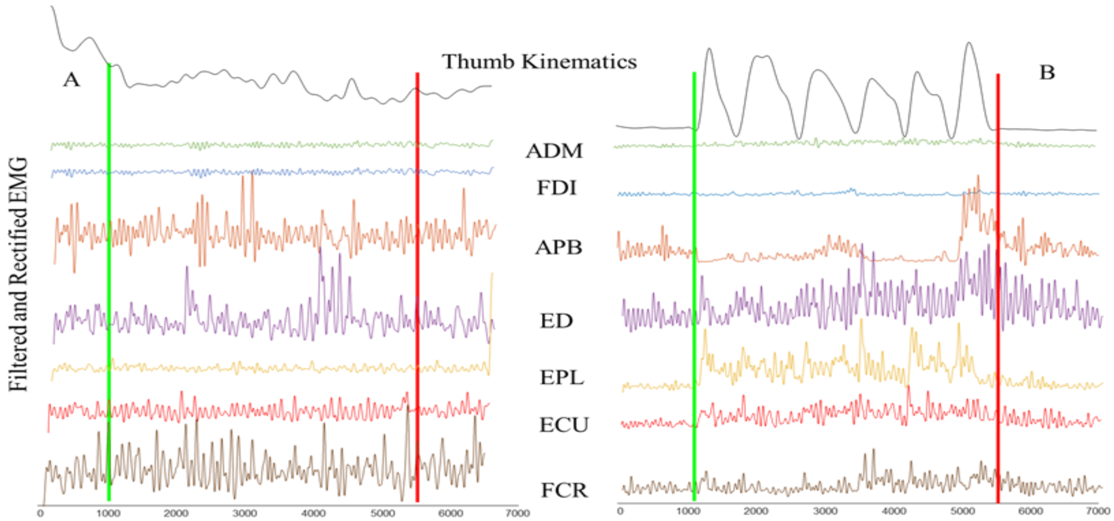


Figure 2.5. Kinematics and sEMG of a participant performing No-tap (A-Trial#12) and Multi-tapping (B-Trial#11) during standing. Green and Red lines represent start and end points, respectively.

Once the Start and End points were identified, the iEMG/time during each of three segments (Start-End, Pre-start, and Post-end) were calculated for all the fourteen muscles for each of the recorded trials. Pre-start was defined by going -200 points from the Start point because this was the period when the thumb was resting on the Home button; as soon as the participants heard the 'Go' signal, they moved their thumb away from the 'Home' button to type the instructed letters. While the post-end segment was defined by going +200 points from the End point because they were instructed to bring their thumb to the 'Home' button after entering the instructed letters. Moreover, these two segments were considered as the segments when the thumb was completely resting and not moving, allowing us to compare the muscle activity across the segment: Pre-start, Start-End and Post-end. iEMG/time for each three segments was averaged across similar conditioned trials (as shown in Appendix M). Averaged iEMG/time from the grasping (no tap) and standing condition was defined as the baseline muscular activity and compared with the averaged iEMG/time for the other nineteen conditions (Appendix M).

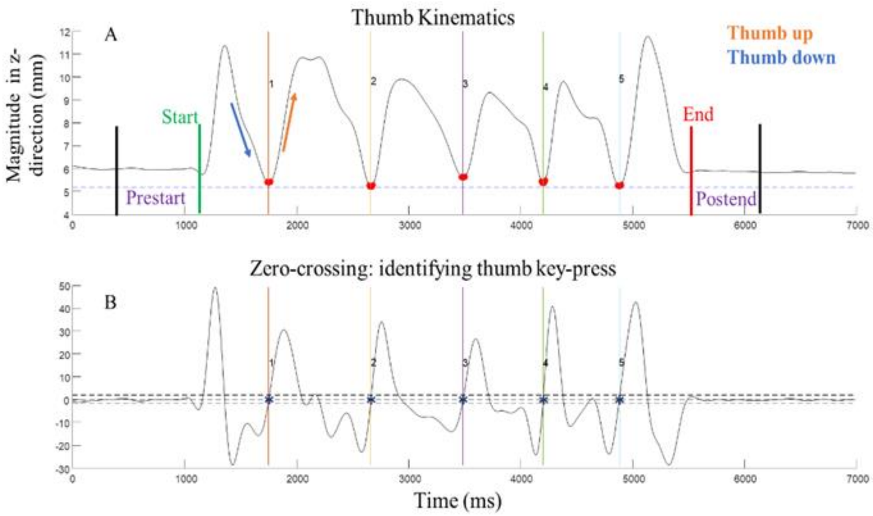


Figure 2.6. A. Thumb local kinematics depicting START and END points, while Red asterisk (*) depicts five thumb keypresses. B. A zero-crossing plot where the blue asterisk (*) represents the thumb keypresses

In this study, the range of amplitude modulation index (AMI) for all the recorded muscles for each condition defining a particular task and movement condition between Start and End points was also calculated to test hypothesis #2 (which was - increased muscle activity of arm and hand muscles would be modulated with the gait cycle due to inertial forces during walking). The amplitude modulation index was defined as the ratio of the amplitude of the modulating signal to the carrier signal (Namuduri and Sen 1986), where the carrier signal was the amplitude normalized EMG signal for the grasping and no tapping (0, 0) and Standing (W0) condition, while the modulating signal was defined as the amplitude normalized EMG signal of all other nineteen conditions such as grasping and tapping (1, 1) and standing (W0), grasping and no-tapping (0, 0) and walking (W80), etc. (see Appendix M for all the conditions). The range of AMI was calculated for similar conditioned trials and later averaged in MATLAB using the range function. Graphs were plotted using Graphpad prism 8.

Statistical Analysis

In this study, there are three independent variables: Grasping with/out tapping task (Task), MCOND, and Segment. Similarly, there were two dependent variables: iEMG/time and the range of AMI. Using SPSS Statistics 26, a 4 (MCOND) x 5 (Task) x 3 (Segment) repeated-measures ANOVA was used to determine whether these three independent variables affected muscular activity measured through iEMG/time with p <0.05 criterion to test hypothesis 1. The summary of the experiment design is shown in table 2.3. Similarly, a 4 (MCOND) x 5 (Task) repeated-measures ANOVA was performed to see whether these MCOND and Task have any effect on the range of amplitude modulation index with p <0.05 criterion to test hypothesis 2 using SPSS statistics 26. Post-hoc comparison tests were performed with a Bonferroni correction test to reveal any statistical significance between multiple comparisons.

Table 2.3. Conditions to be tested

MCOND	**Nature**	**Task**	**Segment**
Standing (W0)/ Slow walking (W80)/ Normal Walking (W100)/ Fastest Walking (W120)	Grasping and no-tapping	No-tap	Pre-start
			Start-End
			Post-end
	Grasping and tapping	Single-tap LR and Single-tap RL	Pre-start
			Start-End
			Post-end
		Multi-tap LR and Multi-tap RL	Pre-start
			Start-End
			Post-end

RESULTS

iEMG/time of Hand muscles

Results of repeated-measures ANOVA was shown in table 2.4. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.7 A) revealed that walking increased iEMG/time compared to standing for FDI and ADM (p<0.05), and normal walking increased

iEMG/time compared to slow walking for APB only (p=0.017). Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.7 B) revealed that iEMG/time for FDI, APB, and ADM were higher during and after compared to before tapping (Start-End, Post-end > Pre-start; $p \leq 0.022$, $p \leq 0.001$, respectively). iEMG/time for FDI and ADM was also higher during compared to after tapping (Start-End >Post-end, $p \leq 0.001$), although APB was lower during compared to after tapping (Start-End <Post-end, p=0.030).

Table 2.4. ANOVA summary table on iEMG/time of Hand muscles

iEMG/time	Effects	(df1, df2)	F	*p*-value	ηp2
FDI	MCOND	1.706, 39.239	10.738	0.000	0.318
	Task	1.277, 29.364	23.974	0.000	0.510
	Segment	1.492, 34.305	33.532	0.000	0.593
	MCOND x Task	4.249, 97.729	1.219	0.307	0.050
	MCOND x Segment	3.240, 74.525	2.483	0.063	0.097
	Task x Segment	2.985, 68.655	17.406	0.000	0.431
	MCOND x Task x Segment	4.052, 93.204	0.781	0.542	0.033
APB	MCOND	2.195, 50.492	3.433	0.036	0.130
	Task	1.639, 37.702	40.298	0.000	0.637
	Segment	2,46	18.458	0.000	0.445
	MCOND x Task	5.473, 125.868	1.231	0.297	0.051
	MCOND x Segment	3.371, 77.53	0.730	0.552	0.031
	Task x Segment	3.976, 91.44	15.629	0.000	0.405
	MCOND x Task x Segment	8.327, 191.516	1.281	0.253	0.053
ADM	MCOND	2.143, 49.298	19.681	0.000	0.461
	Task	2.165, 49.796	31.440	0.000	0.578
	Segment	2,46	35.276	0.000	0.605
	MCOND x Task	5.871, 135.027	1.269	0.277	0.052
	MCOND x Segment	2.877, 66.173	3.645	0.018	0.137
	Task x Segment	3.541, 81.438	18.174	0.000	0.441
	MCOND x Task x Segment	5.078, 116.783	1.167	0.329	0.048

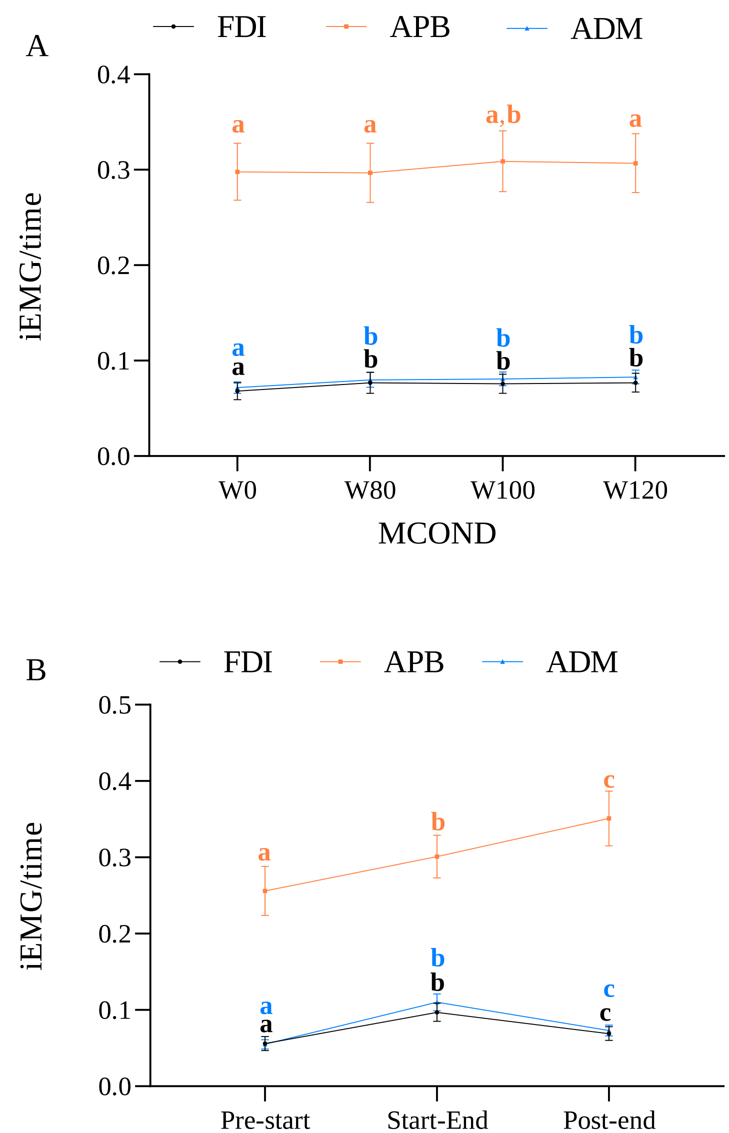


Figure 2.7. Effect of MCOND (A) and Segment (B) on iEMG/time of Hand muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p<0.05$)

iEMG/time of Forearm muscles

Results of repeated-measures ANOVA was shown in table 2.5. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.8 A) revealed that for four recorded forearm muscles, walking increased iEMG/time compared to standing ($p\leq0.048$). For ECU and ED muscles, normal walking resulted in higher iEMG/time compared to Slow walking

($p \leq 0.047$). For ECU, EPL, and ED muscles, Fastest walking resulted in higher iEMG/time compared to Slow walking ($p \leq 0.020$).

Table 2.5. ANOVA summary table on iEMG/time of Forearm muscles

iEMG/time	Effects	(df1, df2)	F	*p*-value	ηp2
FCR	MCOND	1.993, 45.846	5.392	0.008	0.190
	Task	1.775, 40.833	35.859	0.000	0.609
	Segment	1.525, 35.075	38.016	0.000	0.623
	MCOND x Task	5.287, 121.598	1.621	0.156	0.066
	MCOND x Segment	4.237, 97.452	1.726	0.147	0.070
	Task x Segment	2.882, 66.276	25.958	0.000	0.530
	MCOND x Task x Segment	9.013, 207.310	2.131	0.028	0.085
ECU	MCOND	1.967, 45.235	30.050	0.000	0.566
	Task	1.274, 29.31	49.228	0.000	0.682
	Segment	1.256, 28.897	40.330	0.000	0.637
	MCOND x Task	5.344, 122.909	2.106	0.065	0.084
	MCOND x Segment	2.93, 67.399	8.344	0.000	0.266
	Task x Segment	1.512, 34.773	27.638	0.000	0.546
	MCOND x Task x Segment	6.561, 150.894	1.855	0.086	0.075
EPL	MCOND	1.856, 42.697	16.031	0.000	0.411
	Task	1.324, 30.455	53.906	0.000	0.701
	Segment	1.291, 29.684	45.534	0.000	0.664
	MCOND x Task	5.953, 136.928	1.359	0.236	0.056
	MCOND x Segment	6, 138	4.550	0.001	0.165
	Task x Segment	1.778, 40.88	33.834	0.000	0.595
	MCOND x Task x Segment	6.15, 141.442	1.051	0.395	0.044
ED	MCOND	1.961, 45.106	29.196	0.000	0.559
	Task	1.435, 32.994	58.384	0.000	0.717
	Segment	1.355, 31.168	33.303	0.000	0.591
	MCOND x Task	12, 276	1.039	0.413	0.043
	MCOND x Segment	2.922, 67.202	4.242	0.009	0.156
	Task x Segment	3.047, 70.082	19.395	0.000	0.457
	MCOND x Task x Segment	6.351, 146.083	0.882	0.515	0.037

Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.8 B) revealed that for FCR, ECU, EPL, and ED, the iEMG/time was higher during and after compared to before tapping (Start-End, Post-end > Pre-start; $p \leq 0.001$, $p \leq 0.030$ respectively). Likewise, for

FCR, ECU, EPL, and ED, the iEMG/time was higher during compared to after tapping (Start-End > Post-end, $p \leq 0.001$).

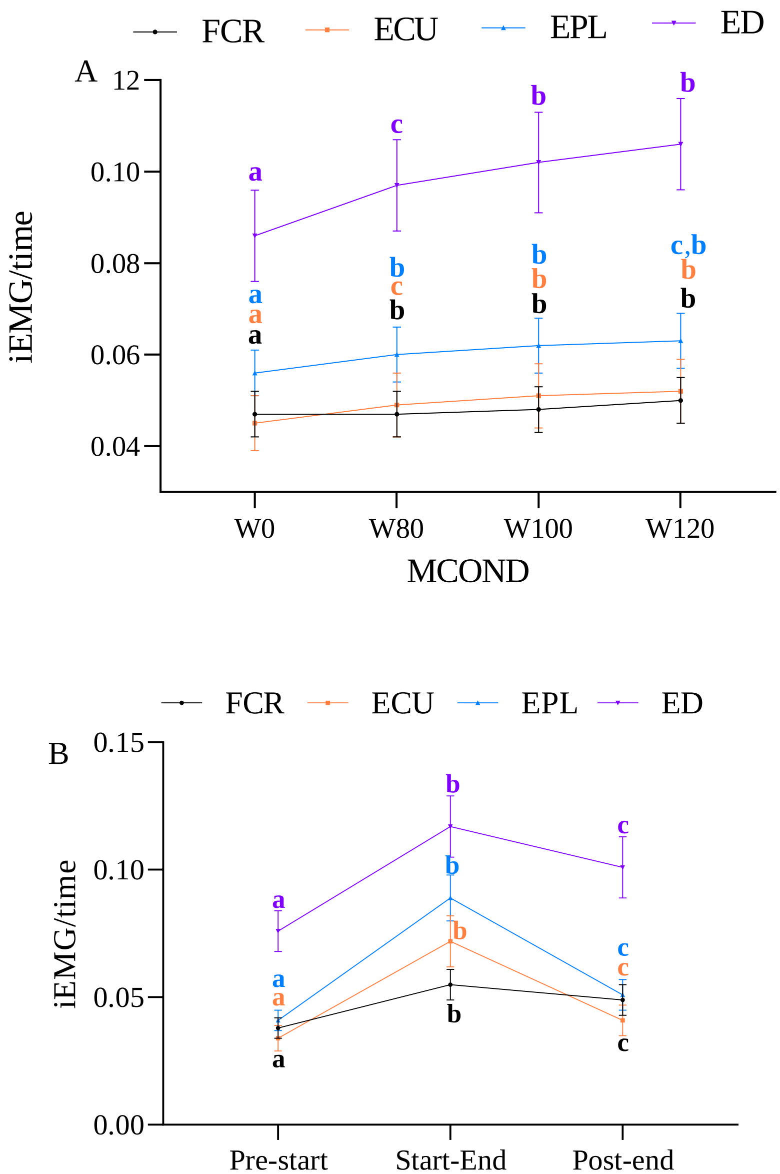


Figure 2.8. Effect of MCOND (A), and Segment (B) on iEMG/time of Forearm muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p<0.05$)

iEMG/time of Upper arm muscles

Results of repeated-measures ANOVA was shown in table 2.5. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.9 A) revealed that walking resulted in higher iEMG/time compared to standing for BIC and TRI muscles ($p \leq 0.006$); Fastest walking resulted in higher iEMG/time compared to Slow walking for BIC and TRI muscles ($p \leq 0.018$). For BIC, the iEMG/time was higher during and after compared to before tapping (Start-End, Post-end > Pre-start; $p=0.001$, $p \leq 0.001$, respectively, (Figure 2.9 B). For BIC, the iEMG/time was lower during compared to after tapping (Start-End <Post-end, $p=0.023$, Figure 2.9 B).

Table 2.6. ANOVA summary table on iEMG/time of Upper arm muscles

iEMG/time	Effects	(df1, df2)	F	*p*-value	ηp2
BIC	MCOND	1.322, 30.396	16.631	0.000	0.420
	Task	1.899, 43.688	8.571	0.001	0.271
	Segment	2, 46	21.248	0.000	0.480
	MCOND x Task	5.181, 119.173	2.264	0.050	0.090
	MCOND x Segment	3.687, 84.812	5.969	0.000	0.206
	Task x Segment	3.799, 87.37	6.479	0.000	0.220
	MCOND x Task x Segment	8.425, 193.779	2.025	0.042	0.081
TRI	MCOND	1.491, 34.303	18.705	0.000	0.449
	Task	2.042, 46.974	1.877	0.164	0.075
	Segment	2,46	2.032	0.143	0.081
	MCOND x Task	5.327, 122.521	1.145	0.340	0.047
	MCOND x Segment	3.911, 89.948	0.705	0.588	0.030
	Task x Segment	5.112, 117.583	2.136	0.064	0.085
	MCOND x Task x Segment	6.079, 139.806	1.511	0.178	0.062

iEMG/time of Shoulder muscles

Results of repeated-measures ANOVA was shown in table 2.7. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.10 A) revealed that for ADEL MDEL and PDEL, walking resulted in higher iEMG/time compared to standing ($p \leq 0.001$). For MDEL and PDEL, normal and fastest walking results in higher iEMG/time compared to slow walking ($p \leq 0.005$). Likewise, the fastest walking increased iEMG/time compared to normal walking for

MDEL muscle (p=0.002). Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.10 B) revealed that for ADEL and MDEL, iEMG/time was higher during Start-End compared to Pre-start ($p \leq 0.001$). For ADEL, the iEMG/time was higher during Start-End compared to Post-end (p=0.001), while for MDEL, the iEMG/time was higher but not significant during Start-End compared to Post-end (p=0.054).

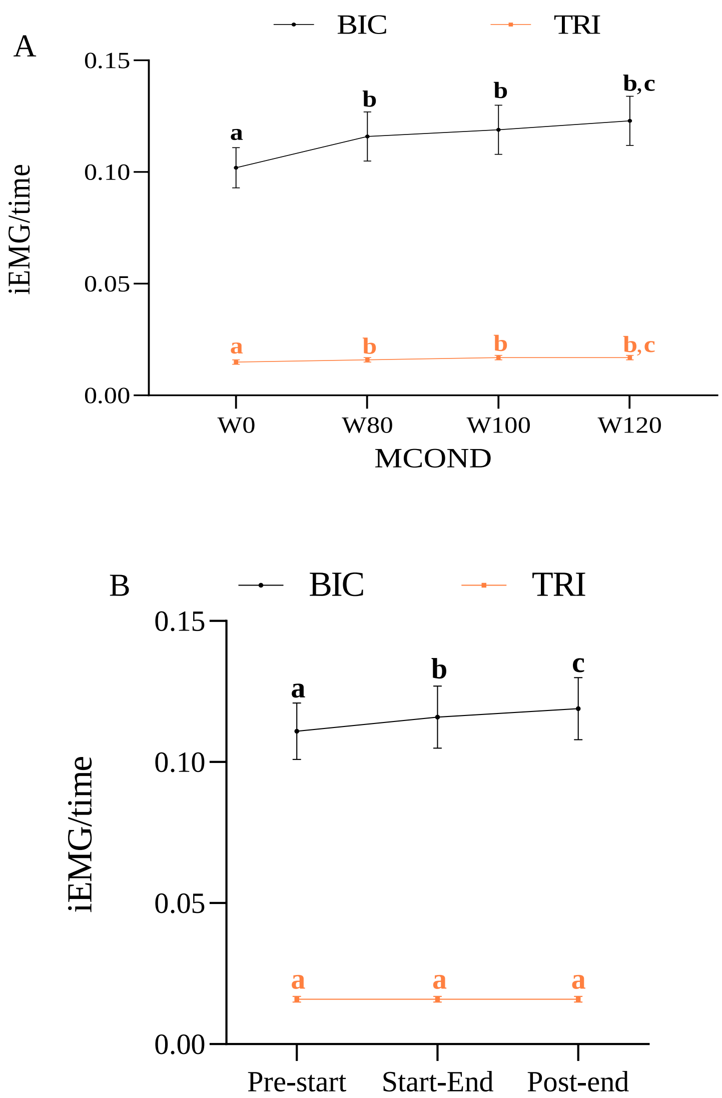


Figure 2.9. Effect of MCOND (A) and Segment (B) on iEMG/time of Upper arm muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups (p<0.05)

Table 2.7. ANOVA summary table on iEMG/time of Shoulder muscles

iEMG/time	**Effects**	**(df1, df2)**	**F**	***p*-value**	**ηp2**
ADEL	MCOND	1.201, 27.626	27.001	0.000	0.540
	Task	1.635, 37.611	14.933	0.000	0.394
	Segment	2,46	11.351	0.000	0.330
	MCOND x Task	6.060, 139.379	2.307	0.037	0.091
	MCOND x Segment	3.494, 80.361	4.269	0.005	0.157
	Task x Segment	3.463, 79.653	5.391	0.001	0.190
	MCOND x Task x Segment	5.515, 126.37	2.201	0.052	0.087
MDEL	MCOND	1.377, 31.671	52.991	0.000	0.697
	Task	2.124, 48.843	5.386	0.007	0.190
	Segment	2,46	9.708	0.000	0.297
	MCOND x Task	6.372, 146.558	1.567	0.156	0.064
	MCOND x Segment	4.367, 100.430	4.822	0.001	0.173
	Task x Segment	4.399, 101.177	5.441	0.000	0.191
	MCOND x Task x Segment	7.797, 179.330	2.348	0.021	0.093
PDEL	MCOND	1.281, 29.453	56.294	0.000	0.710
	Task	1.838, 42.274	0.316	0.712	0.014
	Segment	1.382, 31.780	3.640	0.053	0.137
	MCOND x Task	4.326, 99.508	0.951	0.443	0.040
	MCOND x Segment	2.827, 65.020	1.471	0.232	0.060
	Task x Segment	4.843, 111.39	3.166	0.011	0.121
	MCOND x Task x Segment	6.622, 152.295	1.132	0.346	0.047

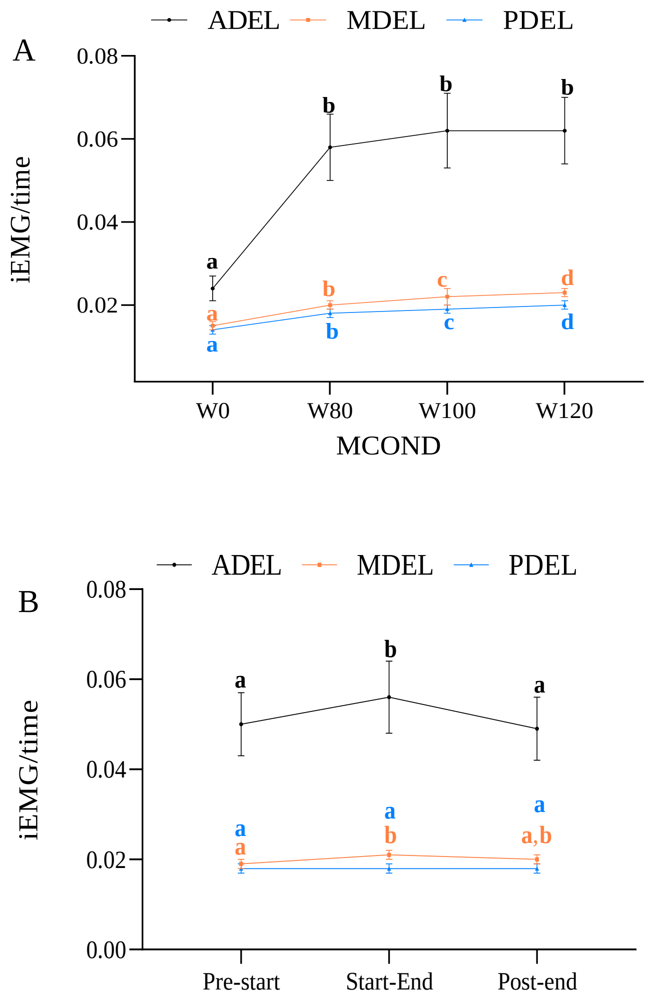


Figure 2.10. Effect of MCOND (A) and Segment (B) on iEMG/time of Shoulder muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p<0.05$)

iEMG/time of Neck muscles

Results of repeated-measures ANOVA was shown in table 2.8. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.11 A) revealed that walking resulted in higher iEMG/time compared to standing for RTRAP and LTRAP muscles ($p \leq 0.001$). For both muscles, normal and fastest walking increased iEMG/time compared to slow walking ($p \leq 0.013$). Similarly, the fastest walking resulted in higher iEMG/time compared to normal walking ($p \leq 0.001$). In contrast, post-hoc tests with Bonferroni pairwise comparison (Figure 2.11 B)

revealed that no significant difference between Start-end compared to Pre-start or Start-End compared to Post-end for RTRAP and LTRAP muscles.

Table 2.8. ANOVA summary table on iEMG/time of Neck muscles

iEMG/time	**Effects**	**(df1, df2)**	**F**	***p*-value**	**ηp2**
RTRAP	MCOND	1.153, 26.524	36.209	0.000	0.612
	Task	2.532, 58.241	10.141	0.000	0.306
	Segment	2, 46	2.043	0.141	0.082
	MCOND x Task	5.943, 136.687	1.636	0.142	0.066
	MCOND x Segment	3.047, 70.077	2.018	0.118	0.081
	Task x Segment	3.864, 88.875	1.342	0.261	0.055
	MCOND x Task x Segment	5.693, 130.943	0.714	0.632	0.030
LTRAP	MCOND	1.154, 26.534	36.374	0.000	0.613
	Task	2.529, 58.157	10.160	0.000	0.306
	Segment	2, 46	2.058	0.139	0.082
	MCOND x Task	5.943, 136.68	1.642	0.141	0.067
	MCOND x Segment	3.041, 69.943	1.997	0.122	0.080
	Task x Segment	3.859, 88.735	1.347	0.260	0.055
	MCOND x Task x Segment	5.688, 130.835	0.709	0.635	0.030

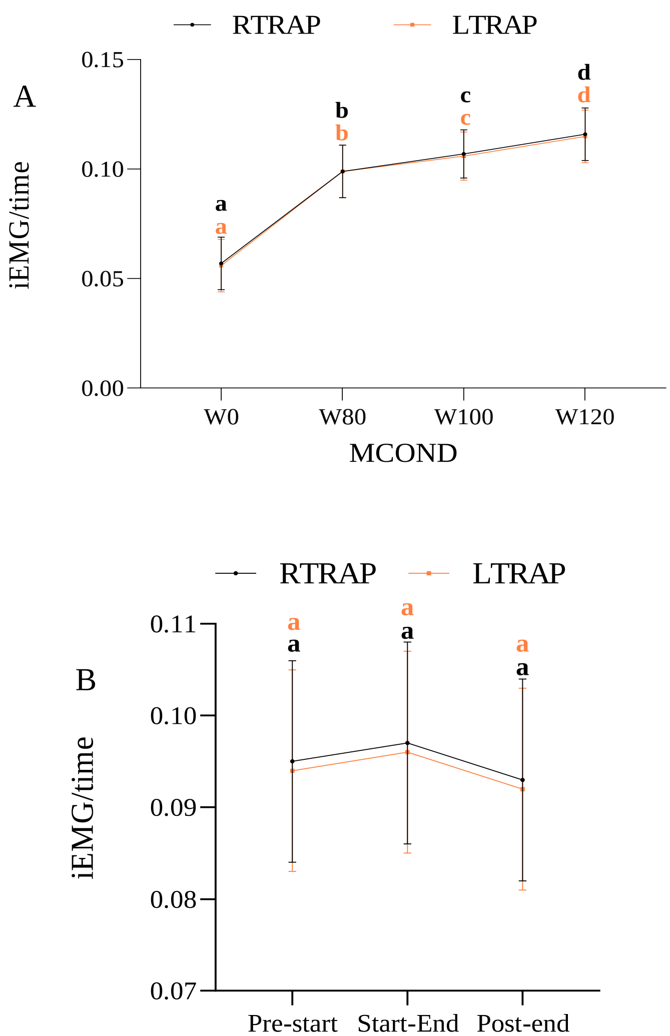


Figure 2.11. Effect of MCOND (A) and Segment (B) on iEMG/time of Neck muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups (p<0.05)

Range of amplitude modulation index (AMI) of Hand muscles

Results of repeated-measures ANOVA was shown in table 2.9. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.12) revealed that walking resulted in a higher range of AMI compared to standing for FDI and ADM muscles (p≤0.004). For Fastest walking resulted in a higher range of AMI compared to slow walking for FDI (p=0.008). Post-hoc tests with Bonferroni correction for pairwise comparisons revealed that walking resulted in a

higher range of AMI compared to standing for FDI and ADM muscles ($p \leq 0.004$). For Fastest walking resulted in a higher range of AMI compared to slow walking for FDI ($p=0.008$).

Table 2.9. ANOVA summary table on range of AMI of Hand muscles

Range of AMI	Effects	(df1, df2)	F	*p*-value	ηp2
FDI	MCOND	1.810, 41.62	18.501	0.000	0.446
	Task	1.209, 27.814	28.02	0.000	0.549
	MCOND x Task	5.599, 128.772	0.958	0.452	0.04
APB	MCOND	2.073, 47.684	2.486	0.092	0.098
	Task	1.245, 28.633	46.897	0.000	0.671
	MCOND x Task	5.434, 124.98	1.201	0.311	0.050
ADM	MCOND	3, 69	11.518	0.000	0.334
	Task	1.301, 29.930	19.279	0.000	0.456
	MCOND x Task	3.177, 73.062	1.316	0.275	0.054

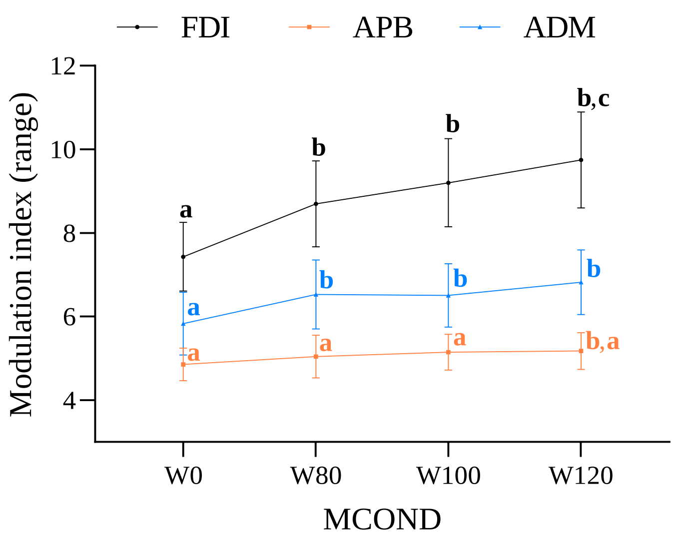


Figure 2.12. Effect of MCOND on range of AMI of Hand muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p<0.05$)

Range of amplitude modulation index (AMI) of Forearm muscles

Results of repeated-measures ANOVA was shown in table 2.10. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.13) revealed that there was a significant main effect on the range of AMI, i.e., the main effect of MCOND and Task on the

range of AMI of all four recorded forearm muscles ($p \le 0.001$). Post-hoc tests with Bonferroni correction for pairwise comparisons revealed that for all four recorded forearm muscles, walking at a different percentage of CWSD resulted in a higher range of AMI compared to standing ($p \le 0.033$). For ECU and ED, the range of AMI for fastest-walking increased compared to the slow walking ($p \le 0.010$).

Table 2.10. ANOVA summary table on range of AMI of Forearm muscles

Range of AMI	**Effects**	**(df1, df2)**	**F**	***p*-value**	**ηp2**
FCR	MCOND	2.053, 47.22	11.916	0.000	0.341
	Task	1.302, 29.940	32.308	0.000	0.584
	MCOND x Task	5.397, 124.137	0.701	0.635	0.030
ECU	MCOND	1.849, 42.522	35.204	0.000	0.605
	Task	1.235, 28.401	55.476	0.000	.707
	MCOND x Task	5.708, 131.284	1.604	0.154	.065
EPL	MCOND	2.348, 53.993	27.142	0.000	0.541
	Task	1.162, 26.734	27.345	0.000	0.543
	MCOND x Task	2.872, 66.063	1.276	0.290	0.053
ED	MCOND	1.699, 39.088	26.945	0.000	0.539
	Task	1.276, 29.35	31.068	0.000	0.575
	MCOND x Task	3.513, 80.808	1.041	0.386	0.043

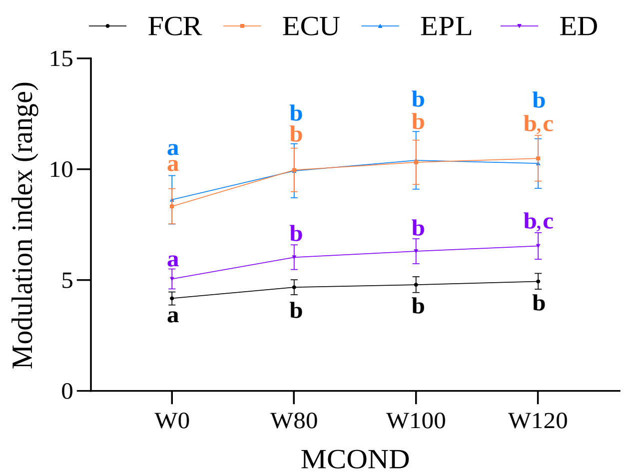


Figure 2.13. Effect of MCOND on range of AMI of Forearm muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p < 0.05$)

Range of amplitude modulation index (AMI) of Upper arm muscles

Results of repeated-measures ANOVA was shown in table 2.11. Post-hoc tests with Bonferroni correction for pairwise comparisons revealed (Figure 2.14) that walking at a different percentage of CWSD resulted in a higher range of AMI compared to standing for BIC and TRI ($p \leq 0.008$). For BIC, the range of AMI was higher for the fastest walking compared to the slow walking ($p \leq 0.001$) and normal walking ($p = 0.019$).

Table 2.11. ANOVA summary table on range of AMI of Upper arm muscles

Range of AMI	Effects	(df1, df2)	F	*p*-value	ηp2
BIC	MCOND	1.851, 42.573	26.742	0.000	0.538
	Task	2.253, 51.824	15.365	0.000	0.401
	MCOND x Task	12, 276	1.694	0.068	0.069
TRI	MCOND	2.133, 49.069	12.213	0.000	0.347
	Task	1.54, 35.413	7.595	0.004	0.248
	MCOND x Task	5.185, 119.256	1.069	0.382	0.044

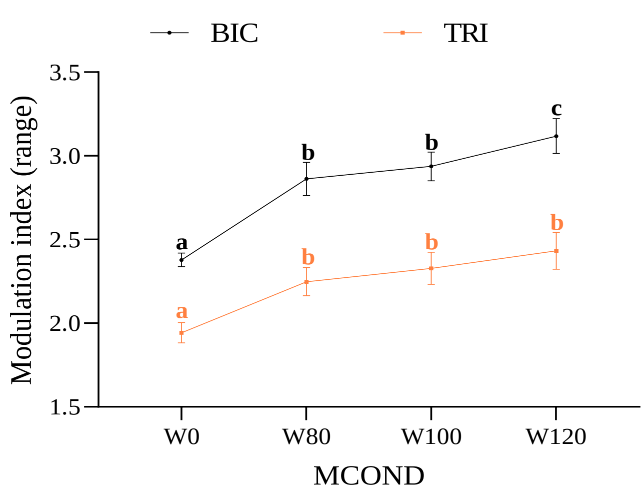


Figure 2.14. Effect of MCOND on range of AMI of Upper arm muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p < 0.05$)

Range of amplitude modulation index (AMI) of Shoulder muscles

Results of repeated-measures ANOVA was shown in table 2.12. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.15) revealed that walking at a different percentage of CWSD resulted in a higher range of AMI compared to standing for all three deltoid muscles ($p \leq 0.001$). In addition, the range of AMI was higher for the fastest walking compared to the slow walking for all three deltoid muscles ($p \leq 0.048$).

Table 2.12. ANOVA summary table on range of AMI of Shoulder muscles

Range of AMI	Effects	(df1, df2)	F	*p*-value	ηp2
ADEL	MCOND	1.218, 28.021	43.454	0.000	0.654
	Task	1.52, 34.97	7.095	0.005	0.236
	MCOND x Task	5.192, 119.418	1.628	0.155	0.066
MDEL	MCOND	1.598, 36.755	32.972	0.000	0.589
	Task	1.925, 44.267	12.004	0.000	0.343
	MCOND x Task	4.528, 104.143	2.642	0.032	0.103
PDEL	MCOND	1.282, 29.484	30.365	0.000	0.569
	Task	1.345, 30.927	9.744	0.002	0.298
	MCOND x Task	2.213, 48.831	2.249	0.113	0.089

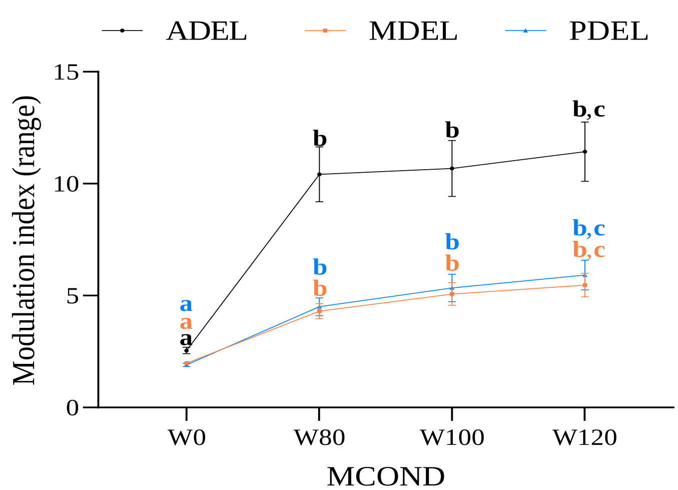


Figure 2.15. Effect of MCOND on range of AMI of Shoulder muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p<0.05$)

Range of amplitude modulation index (AMI) of Neck muscles

Results of repeated-measures ANOVA was shown in table 2.13. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 2.16) revealed that walking at a different percentage of CWSD resulted in a higher range of AMI compared to standing for both RTRAP and LTRAP muscles ($p \leq 0.001$). Both RTRAP and LTRAP muscles showed a higher range of AMI for the fastest walking compared to normal or slow walking ($p \leq 0.007$). Likewise, RTRAP and LTRAP muscles showed a higher range of AMI for normal walking compared to slow walking ($p \leq 0.006$).

Table 2.13. ANOVA summary table on range of AMI of Neck muscles

Range of AMI	Effects	(df1, df2)	F	p-value	ηp2
RTRAP	MCOND	1.124, 25.860	26.694	0.000	0.537
	Task	1.455, 33.468	3.006	0.078	0.116
	MCOND x Task	4.549, 104.635	0.596	0.688	0.025
LTRAP	MCOND	1.12, 25.753	25.923	0.000	0.53
	Task	1.442, 33.175	2.946	0.081	0.114
	MCOND x Task	4.506, 103.648	0.589	0.691	0.025

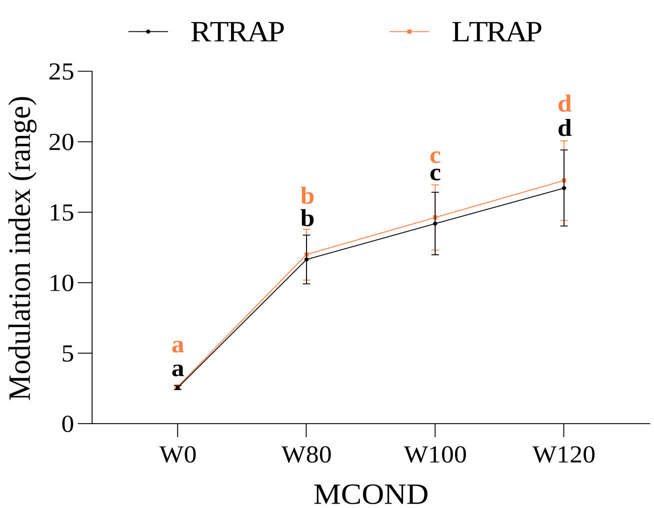


Figure 2.16. Effect of MCOND on range of AMI of Neck muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p<0.05$)

DISCUSSION

We examined the neuromuscular control of the upper limb during grasping and tapping tasks executed with a handheld smartphone device by evaluating muscle-activation patterns of the upper limb during different movement conditions, i.e., standing and walking at a different percentage of CWSD. We found that the muscle activity in all recorded muscles was altered for movement conditions, while the patterns of change concerning segments differed among the muscles.

Effect of Segment

The first hypothesis that arm and hand muscle activity would increase before the thumb begins tapping and be maintained at the increased level until thumb returns to start position was partially supported. We found that muscle activity in all the recorded intrinsic hand and forearm muscles, as well as one upper arm (BIC) and two shoulder (ADEL and MDEL) muscles, was elevated during tapping and decreased after tapping ceased except for activity in APB, BIC, and MDEL that remained elevated or increased regardless of movement condition or segment. Increasing muscle activity of specific muscles during tapping tasks compared to before tapping began would be the strategy used to accomplish the additional layers of motor tasks associated with smartphone manipulation beyond grasping, such as tapping and maintenance of the upper limb posture. As texting requires repetitive thumb movement away from and onto the surface to tap keys, the thumb action could destabilize the device with a one-handed thumb grip (Eardley et al. 2018). Both intrinsic and extrinsic hand muscles increased their activity, which could be attributed to the need to provide a better grip and stabilize the device (Gysin et al. 2003). This is consistent with previous studies that have examined the intrinsic hand muscles activity during hand-object interaction and have found that activity in these muscles is associated with control of

the digits and better grip and object stabilization (Johanson et al. 2001; Maier and Hepp-Reymond, 1995; Schieber, 1995; Winges et al. 2007). Other smartphone studies have also demonstrated altered activity in intrinsic hand muscles (FDI, APB, and ADM) when tapping on different button size, thumb movement direction (Xiong and Muraki, 2014; Xiong and Muraki, 2016), one-handed versus two-handed smartphone manipulation (Xie et al. 2016) while maintaining different body positions like sitting and standing and while texting and talking (Gustafsson et al. 2010; Kim et al. 2016), and hand size (Ahn et al. 2016).

Another layer of motor tasks pertinent during one-handed smartphone manipulation is to maintain the posture of the upper limb and simultaneously support the hand for grasping and tapping regardless of movement condition. All the recorded forearm muscles (FCR, ECU, ED), one upper arm (BIC) and two shoulder muscles (ADEL and MDEL) increased their activity during the tapping task compared to before tapping. Based on this, it suggests that the proximal and distal segments (shoulder, elbow and wrist joints) increased their joint stiffness to maintain the upper limb position and dampen the influence of inertial forces when walking in addition to the instability generated from the thumb movement (Gustafsson et al. 2011; Kietrys et al. 2015; Maier and Hepp-Reymond 1995; Mizrahi et al. 2017; Roth et al. 2011; Song et al. 2020; Togo et al. 2012; Togo et al. 2014; Togo et al. 2015; van Oudenaarde et al. 1997; von Werder and Disselhorst-Klug 2016). Our study's result showed that the activity of the EPL muscle increased during tapping, suggesting that EPL muscle is directly influenced by the thumb motion-tapping, which involves flexion/extension (Flex/Ext), and adduction/abduction (Ad/Ab) of the thumb. This is consistent with previous studies as they found EPL and APL (abductor pollicis longus) muscles getting activated with thumb movement (van Oudenaarde et al. 1997) and during one-handed thumb tapping while walking (Hong et al. 2013; Kim et al. 2018).

With this study, we also investigated muscle activity after tapping. Our result showed that the activity of FDI, ADM, FCR, ECU, EPL, ED, and ADEL muscles lowered after tapping except for APB, BIC, and MDEL muscles. These two muscles (APB, BIC) maintained their greater activation after tapping. This result is not consistent with a previous study, which showed that a decreased in the activity of thumb and neck muscles after sending a text message (Lin and Peper 2009). One possible explanation for the continued increment in the activity of APB muscle could be that participants were instructed to rest their thumb at the 'Home' button after the tapping. Hence, they could have flexed the IP joint of the thumb vertical rather than the oblique resulting increment in APB muscle after tapping. Further, it was instructed to participants to maintain/flex their elbow after tapping for a few seconds to allow the PI to stop the recording, which could have resulted in an increment in BIC muscle. In the case of MDEL muscle, participants kept their arm away from the trunk during tapping; once it was over, they could have adducted the arm by bringing it closer to the trunk, which did decrease MDEL muscle activity but not to a significant level.

On the other hand, our result showed that the activity in the posterior arm, shoulder, and neck muscles (TRI, PDEL, RTRAP, and LTRAP) did not change significantly during the task. Smartphone users might have stabilized head and neck while simultaneously maintained shoulder flexion and abduction along with elbow flexion (Cook and Kothiyal 1998; Landin and Thompson 2011). Their elbows and forearm were unsupported (Cook et al. 2004), so maintenance of such posture could have resulted in constant muscle loading (contraction) of these four muscles (TRI, PDEL, and R/LTRAP) during one-handed smartphone interaction across both standing and walking conditions. On the contrary, one study found significantly higher mean EMG activity from the right upper and lower TRAP and PDEL muscles when using

a standard keyboard. This study suggested that this increment could have been the requirement of the arm abduction compared to the centrally positioned trackball (Harvey and Peper 1997). Others have found that activity in the R/LTRAP muscles was lower in the group who used forearm support during texting (on the phone) and typing (on the computer) compared to the group without forearm support (Cook et al. 2004; Gustafsson et al. 2011). Compared to this, our participants maintained their limb without any support during standing and walking. On the other hand, there was a study that showed there was a continuous but diminished EMG activity of TRI, ADEL, and PDEL muscles when arm immobilized with a brace during which they found the similar activity to the normal gait performed without arm constrained. This arm-bound condition draws some parallelism to one-handed smartphone manipulation as in both cases, the upper arm is held flexed, and almost abducted (Kuhtz-Buschbeck and Frendel 2015).

The results presented here are a novel addition to the existing literature suggesting that our neuromuscular system does not necessarily anticipate and continuously increase the muscle activity of the upper limb during smartphone manipulation. Rather, depending upon the segments (phases) of a trial involving grasping with/out tapping, it would generate motor commands that would vary the magnitude of the muscle activation of the upper limb, helping to accomplish a complex multi-layered motor task such as grasping, tapping, and stabilization of the upper limb.

Effect of movement condition

The second hypothesis that the muscular activity of both arm and hand muscles would be increased and modulated with the gait cycle and as walking speed increases, the gain of the modulation will also increase was supported. We found that the average muscle activity (iEMG/time) of all fourteen recorded muscles was significantly higher for different percentages of CWSD compared to standing. Likewise, we also found that the range of amplitude modulation

index was significantly higher for different percentages of CWSD compared to standing for thirteen recorded muscles except for APB. There was a mixed effect when the different percentage of CWSD was analyzed for both average muscle activity (iEMG/time) and range of amplitude modulation index. These changes in muscle activity appear to be a strategy to dampen arm movement generated from the inertial forces acting on the hand and arm due to walking, thus preventing instability of the smartphone (Gysin et al. 2003; von Werder and Disselhorst-Klug 2016). This is consistent with previous studies where they have suggested that our neuromuscular system finds a suitable way of controlling tasks with a distal segment like prehension while simultaneously maintaining the upper arm and forearm posture during object transport. Such a controlling mechanism was understood with surface EMG recordings (Carnahan et al. 1996; Gribble et al. 2003; Mizrahi et al. 2017; Roth et al. 2011; Togo et al. 2012; Togo et al. 2014; Togo et al. 2015). In addition, increased activation in the upper limb muscles could improve the device grip and subsequently, moderate the device instability coming from downward moving thumb taps onto the device (Eardley et al. 2018; Gustafsson et al. 2011) and arm swing when walking at varying speeds compared to standing. Schildbach and Rukzio (2010) suggested that it becomes difficult to read/tap the keys during walking, so this dampening strategy could make us easier to interact with our smartphone devices during walking compared to standing.

This result is consistent with a previous study where hand (FDI, ADM) and arm-shoulder muscles (BIC, TRI, ADEL, PDEL) were significantly recruited to accomplish multi-digit object manipulation involving grasping and transportation of a cylinder (Winges et al. 2007) except for APB. Our result showed that for APB, the movement condition (MCOND) had a different effect on the average muscle activity (iEMG/time) and no effect on the range of amplitude modulation

index. This discrepancy is likely due to the role of the thumb, wherein most of the multi-digit grasping the thumb is used to stabilize the object with the help of other digits, but in our case, the thumb is either floated over the touchscreen (as it is free to press the keys) (Bullock and Dollar 2011) or rested upon the home button. This change in thumb role, frequent thumb contact compared to the repetitive but not continuous thumb contact would require different activation patterns. One similar study examined the effect of smartphone usage on the muscles of the upper limb while standing, walking, and standing on an unstable position (Kim et al. 2018). They have found the APB muscle activity during the one-handed operation was higher than TRAP and EPL, during standing and walking. They further found that the APB muscle continued to show higher muscle activity during walking than standing, which contrasts with our results where APB did not change between standing and walking (Kim et al. 2018). Based upon the results, this study has shown that there is distinct muscle activation for walking versus standing when the upper limb is involved in one-handed smartphone manipulation; however, such distinctiveness disappears when the comparison was made between different speed levels.

In short, standing or walking with a smartphone is an example of asymmetric but negligible load-carrying tasks. Depending upon the different segments (phases) of the trials involving grasping with/out tapping and MCONDs, our neuromuscular system uses a differential motor control strategy that consistently generates a multi-muscle activation pattern by utilizing the existing degrees of freedom available in the upper limb that would help in grasping and tapping and maintain dynamics of the arm according to the movement conditions.

CHAPTER 3. EFFECT OF ARM HEIGHT: STUDY 2

INTRODUCTION

In the first study, we compared the muscle activity during different segments of the trials involving grasping with/out tapping and MCOND. Our neuromuscular system intelligently varies the multi-muscle activation pattern of the upper limb depending upon the segment of the trials involving grasping with/out tapping and MCOND. Besides texting, smartphone users nowadays read and take pictures using these devices. Such cellular actions could require different arm height, such as in case of a 'selfie' position where the arm either is held in a fully extended position or little flexed at the elbow compared to the texting. One study has shown that people maintain such posture frequently and until a good photo is taken (Khanal et al. 2019), which could result in a condition similar to 'text neck' or 'text thumb.' Such repetitive position could put excessive loading on the muscles of the upper limb and could strain the elbow and wrist joint (Khanal et al. 2019). Hence, the primary goal of the second study was to understand the muscle loading that is generated when smartphones are manipulated at two comfortable arm heights: shoulder and abdomen by recording the 14 muscles of the upper limb while maintaining tapping and movement conditions. Similarly, this study also examined the interaction effect of movement condition and arm height on the muscle activity of the upper limb involved in smartphone manipulation. Its result could give us an idea about which of this two-arm height would be an optimum smartphone holding positions to avoid any discomfort in arm and neck-shoulder regions (Guan et al. 2016; Xie et al. 2018) during smartphone manipulation. Moreover, it would also help us to understand how these two-arm heights would influence the motor control strategy generated by our neuromuscular system for optimum smartphone manipulations during movement. Thus, the purpose of this study was to examine how muscle activity changes when a

smartphone is held at two different arm heights, i.e., the hand is either at shoulder level or abdomen, as shown in figure 3.5. Past studies using smartphones examined muscle activity of the upper limb and neck when the smartphone was held and operated either at the chest height to execute uni/bilateral texting (Xie et al. 2016) or from different locations, flat table surface and in hand (Ning et al. 2015). However, these studies did not examine the effect of holding the device at different levels and how these two placements of smartphone holding could influence the neuromuscular control strategies required for hand and arm involved in smartphone manipulation while simultaneously maintaining MCOND. We hypothesized that when manipulating a smartphone device at the shoulder level, there would be an overall increase in arm muscle activity to stabilize the arm and overcome the moment. We also hypothesized that the hand muscles would show a similar significant increase in muscular activity when the device was manipulated at the shoulder level compared to the abdomen level. This gain in the muscular activity of the hand muscles would prevent slippage of the device in a potentially less stable arm posture. Finally, we hypothesized that walking would result in greater muscular activation patterns across both hand and arm muscles compared to standing when the device is held at the shoulder level compared to the abdomen. This is because walking results in greater perturbation of the arm and device, especially in the more extended shoulder level position, therefore greater muscle activity would be required to prevent instability of the arm and the device.

METHODS

Participants

Twenty-one students (5 males and 16 females) age range from 20 to 23 years (M=20.95, SD=0.80), height range from 1.56 to 1.88 m (M=1.69, SD=0.07) and weight range from 46.5 to 113.3 kg (M=68.55, SD=14.82) were recruited from Louisiana State University (LSU) with no

self-reported neuromuscular, or orthopedic history. Participants were tested for Finkelstein and Phalen's test to confirm whether they have any irritation or pain at/around the base of the thumb and in their carpal tunnel and medial nerve in the wrist due to excessive usage of the smartphones respectively. They showed a negative result for the Finkelstein and Phalen's test (Appendix C). They also self-reported either normal or corrected to normal vision (Appendix F). Based on the online questionnaire response, participants have been using their smartphones for a minimum of four years to more than ten years (Appendix H). Edinburgh handedness inventory test (Appendix I) showed that five participants were ambidextrous ($-40 \leq R \leq +40$), while the other sixteen participants were right-handed ($R > +40$) (Appendix F). Participants signed the consent form approved by the LSU Institutional Review Board (IRB) (Appendix A). They were given an extra-credit for their participation in one of their kinesiology classes at the University. The experiment lasted three hours.

Hand and arm anthropometry data of each participant were measured, as shown in figure 2.1 and summarized in table 3.1 (see Appendix G for each participant's demographics, hand and arm anthropometric data and handedness test details). In addition, shoulder height, and two arm lengths were also measured. Shoulder height was defined as the vertical distance from the floor to the acromion or the bony tip of the shoulder (S), as shown in figure 3.1 (A) (Koroemer 2001). Similarly, Arm length 1 was defined as the distance between the acromion of the shoulder to the metacarpophalangeal (MCP) of the index finger (MCPI) such that the arm and the wrist were kept neutral and the fingers were folded (made a fist) to identify the MCPI crease shown in figure 3.1 (B). In this position, participants maintained an upright position of their body, held their arm straight in front (fully extended) such that the shoulder's acromion marker and MCPI's marker are in a straight line (or approximately at the same height from the ground). The primary

reason for selecting MCPI crease as a point was because it is the most likely position the phone will rest when we hold the device in our hand, giving approximation as to where the device's screen will be located from the body.

The second arm length (arm length 2) was also defined as the distance between the acromion of the shoulder to the MCPI; however, this distance was measured when the arm was slightly flexed as shown in figure 3.1 (C), making this distance smaller than the first arm length. During this measurement, the participants were handed the experimental device and given the following verbal instruction: "Imagine that you are going to take a selfie by holding the device at the shoulder level such that the markers of MCPI and shoulder are at the same level and the device should be held at a comfortable distance; the arm should not be fully stretched or fully collapsed." Upon receiving these instructions, participants found their comfortable arm length 2. Once they identified a comfortable arm length 2, the shoulder and MCPI markers were checked for alignment (at the same height) while they held the device using a ruler. If necessary, a ruler was used to keep the acromion and the MCPI at the same level, but as shown in figure 3.1 (C), comfortable arm length 2 was defined by the subject individually. Arm-length 2 distance was measured thrice and the average of the measured values defined as arm-length 2. Later, participants were instructed to maintain this distance while keeping the MCPI at shoulder level for all the shoulder position trials. For the abdomen condition, participants were instructed to position their device such that the MCPI marker was in between the xiphoid process of the sternum's marker (T) and the hip (H) marker, as shown in figure 3.5 (B).

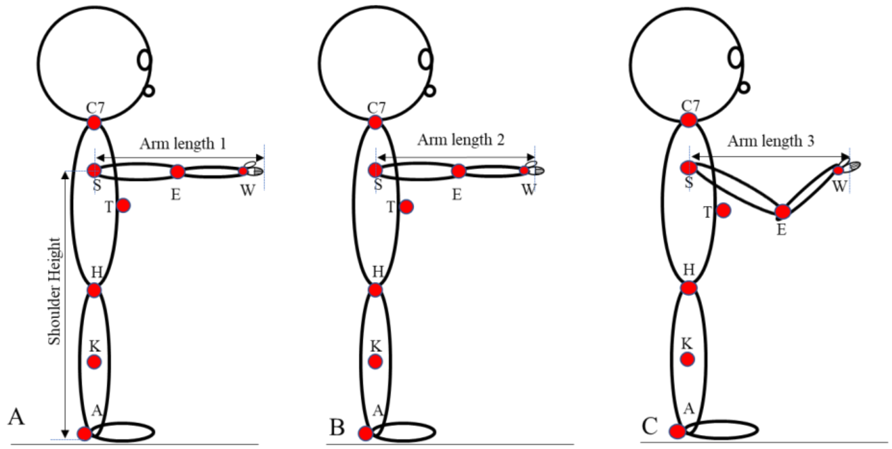


Figure 3.1. A. Shoulder height and arm length 1 measurement. B. Arm length 2 measurement when arm extended at the shoulder level. C. Arm length 3 measurement to hold the device at the shoulder level. S=Shoulder, E= Elbow, W=Wrist, H=Hip, K= Knee, A=Ankle, and T= Xiphoid process of the sternum

Table 3.1. Anthropometric data for hand and arm length in centimeters

#	Dimension	Mean (SD)		Dimension	Mean (SD)
1	Hand length	17.69(0.83)	7	Thumb circumference	7.65(10.97)
2	Palm length	10.06(0.47)	8	Arm Length 1	72.25(4.3)
3	Distal handbreadth	8.26 (0.69)	9	Shoulder height	140.9(7.06)
4	Maximum handbreadth	9.93(0.66)	10	Arm length 2	61.84 (3.17)
5	Thumb length	6.08(0.38)	11	Arm length 3	46.30 (4.80)

Surface electromyography (sEMG) data collection apparatus

Surface electromyography (sEMG) data were collected using a 16 channel EMG system (MA 400-28) and two types of EMG preamplifiers, MA-411 and MA-422 (Motion Lab System, Baton Rouge, LA), to record the muscle activity of the hand (FDI, APB, ADM), forearm (FCR, ECU, EPL, ED), upper arm (BIC, TRI), shoulder (ADEL, MDEL, PDEL) and neck region (RTRAP, LTRAP). EMG preamplifier MA-422 was attached with a pair of disposable GS26 Pre-Gelled Disposable sEMG Electrodes (Bio-Medical Instruments, MI) while EMG preamplifier MA-411 has two 12-mm medical-grade stainless-steel disk electrodes and it does not require any electrode cream or gel. Each muscle was prepared: palpated, shaved if needed, abraded, and cleaned using alcohol and cotton before the electrode placement. These electrodes

placement areas were determined using Surface EMG Non-Invasive Assessment of Muscles (SENIAM) guidelines (Hermens et al. 2000) or a book titled as Anatomical Guide for the Electromyographer The Limbs and Trunk (Perotto 2011) (Appendix J). EMG signals were collected at a sampling rate of 2400 Hz.

Kinematic data collection apparatus

Participant's upper and lower body movements, along with the smartphone movement, were captured by the Oqus-300 motion capture system (Qualisys, Gothenburg, Sweden). Kinematic data were collected at 120 Hz. There were eight cameras, which were spread around the treadmill. Passive 38 retroreflective hemispheric markers (of 9.5 mm and 25.4 mm in diameters) were placed on the following landmarks for the kinematic data recordings: tragi, canthi, glabella, spinous process of the 7th cervical vertebrae, acromia, manubrium, and xiphoid process of the sternum, lateral humerous epicondyles, greater trochanters, medial ½ of the right femur, lateral femoral condyles, lateral malleoli, calcanei, styloid processes of radius and ulnar, distal phalange, interphalangeal, metacarpophalangeal and carpometacarpal of the thumb, heads of metacarpals and bases of the second and the fifth digits (Lee and Jung 2014), the dorsal side of the radius and ulnar of the forearm and the edges of the device (Appendix L). These markers were placed on the skin using double-sided tape except the markers of the feet (which were placed on the participant's shoes outer sole) and the device (which were placed on the edges of the device as shown in figure 2.3). Before the actual trial recording began, PI made sure that all the 38 markers were visible by the cameras such that the visibility of the markers (fill level) were appropriately 100%. Figure 3.2, 2.2, and 2.3 showed the placement of the markers on the human body, and the smartphone device, respectively.

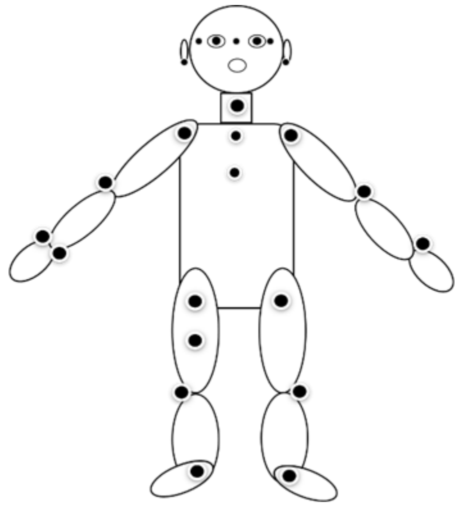


Figure 3.2. A human model with passive markers

Handheld mobile device

An LG Leon smartphone device designed and manufactured by LG electronics was used as a handheld mobile device for this study (Figure 2.3). Its dimension was 5.11" (H) x 2.55" (W) x 0.43" (D). had a screen size of 4.5 " full wide VGA display with a screen resolution of 854 x 480 pixels. Its total weight was 120 gm (4.89 oz.).

Experimental conditions: Grasping with/out tapping task

There were two tasks; The first task was defined as a Grasping and no-tap, and it was considered as a static (trials) reference for EMG. While the other task was defined as Grasping and tapping task and included two multi-tap tasks and were considered as dynamic trials. Participants were instructed to type as naturally as possible at their comfortable typing speed as they would do in their daily living. They were also instructed to type accurately. In case if they made an error, they would inform the PI and redo the trial. Further, they were instructed to ignore the letter case while typing and were not allowed to use the automatic word completion function. For the Grasping and no-tap, kinematics and EMG data were recorded when participants rested their thumb on the logo, as shown in figure 2.4 for approximately 5-6 seconds.

They looked at the screen of the smartphone device by focusing on the letter ‘G’ of the keypad. Once the recording was over, they removed their thumb from the ‘Home’ position and relaxed. Once the recording was over, they removed their thumb from the ‘Home’ button and relaxed.

On the other hand, Grasping and tapping task trials included two multi-tap tasks with a 2-3 seconds pause in between the two multi-tap tasks. For example, participants moved their thumb from the ‘Home’ button to tap the first five single target letters (QGMGQ) diagonally positioned from Left to Right (LR) (NW, NorthWest ↔ SE, SouthEast) direction. Once they finished entering the first five letters, they rested their thumb on to the ‘Home’ button for 2-3 seconds. Afterward, they moved their thumb from the ‘Home’ button to type the second five target letters (PGZGP) diagonally positioned from Right to Left (RL) (NE, NorthEast ↔ SW, SouthWest) direction. They rested their thumb on the ‘Home’ button once they finished entering the second sequence. These two tapping tasks done in one single trial were divided into halves during offline using QTM software and analyzed separately as two multi-tap tasks. These target letters are highlighted on the device shown in figure 2.3.

Table 3.2 summarized all the tasks and the number of trials to be executed in one block. These tasks were reminded by the primary investigator (PI) verbally and visually through a computer monitor placed in front at a distance of 52" and at the height of 45". Participants rested their thumb on the ‘Home’ button of the device, as shown in figure 2.4, before and after a tapping task was over. Recording of Kinematics and EMG signals began a few seconds prior to the ‘Go’ cue from the PI. With this signal, participants started their task. Once the task was over, they spoke loudly, ‘Done,’ and the recording was stopped. All the tasks were recorded in the note-taker application of the given device.

Table 3.2. Smartphone manipulation Task

Nature	Task	Executed task	# of Trials
Grasping	No-tap	Thumb rested at 'H'	5
Grasping and tapping	Multi-tap (Pseudo-text)	H‣QGMGQ‣H‣PGZGP‣H	5

Note 1) H means 'Home' of the smartphone device (LG logo).

Experimental conditions: Arm height

There were two arm heights in this study. These arm heights were defined as the shoulder and abdomen position. Participants were instructed to hold the device either at the shoulder or abdomen position while simultaneously, they were required to do the tapping tasks and maintain the movement conditions. Participants were constantly reminded about the arm heights and where they have to maintain/hold the device before a trial recording. Participants were also instructed not to keep their arm and elbow close (rested) to their trunk and avoid any support to the arm and elbow. They were also instructed to keep their arm and hand holding the device straight-ahead/in front such that the arm is in between the medial and lateral (imaginary blue) line drawn from the sternum and shoulder, as shown in figure 3.3 (Dean and Shepherd 1997; Varghese et al. 2015).

Experimental conditions: Movement Condition

These two arm heights and three tasks were performed during standing and walking at a different percentage of comfortable walking speed with the device (CWSD) on a treadmill (Bertec Instrumented Treadmills, 1.75 x 0.5 (m) each, and approx. 0.4 m above the ground). Participant's comfortable walking speed with the device (CWSD) and without the device (CWS) was described in the first study. Once the CWSD or the normal walking (W100) was identified, the other two speeds: slow and fastest walking speed was also calculated as 80% of CWSD and 120% of CWSD, respectively. The average CWSD ranged between 1.80 and 2.88 (*M*=2.40,

SD=0.33 kmph) while the average CWS ranged between 2.16 and 4.32 (*M*=2.98, *SD*=0.58 kmph). For their safety purpose, there were handrails, and the helper standing nearby in case of falling situation comes during a walking trial. Before the actual trial recording began, each participant was allowed to tap on the device while simultaneously maintain standing or three walking conditions to help them to acclimatize in the given environment.

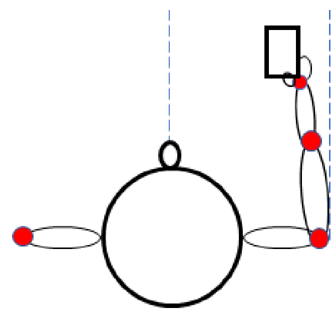


Figure 3.3. Smartphone held in between the medial and the lateral line drawn from the shoulder marker/acromion (Top view)

Dependent Variable

Mean muscular activity (μV) (Mean EMG) of all the recorded muscles was used to quantify the EMG signals of each trial. In this study, the mean muscular activity was found out between the Start and End points, where the Start and Endpoints are identified as described in the first study. Once the mean muscular activity of all the recorded muscles of each trial has been calculated, these mean EMG values are grouped and averaged based upon the reference values created for a condition defining a particular task, movement condition, and arm height (Appendix M). Shoulder and elbow joint angles (in degrees) were calculated to find the flexion and extension of the shoulder and elbow joint during each trial. These two joint angles would help to correlate the effect of the arm heights on the muscular activity of the upper limb during smartphone manipulation tasks such as tapping and no-tapping over different movement conditions. Another dependent variable analyzed was the slope angle. The slope angle

differentiated whether a trial was done by holding the hand at the shoulder or the abdomen position. This would further help to understand the effect of the shoulder and abdomen position on the muscular activity of the upper limb. Further, the z-coordinate ratio and coefficient of variation (COV) were also analyzed.

General Procedure

Once the participant arrived in the lab, s/he was explained about the purpose and procedure of the study. They signed the consent form and then fill out the questionnaire, and the Edinburgh handedness inventory test. They were measured for their hand, shoulder-length, shoulder height, and arm length 1 measurement and followed by the Finkelstein test (Thumb), and Phalen’s test (Wrist). Participants were also explained about the shoulder and abdomen positions and how they were defined. Their comfortable arm length 2 was recorded three times, and their average value was found out to define the position where the participants had to hold the device for the shoulder position trials during recording.

Afterward, they were applied with the fourteen EMG electrodes and thirty-five markers on their body. Before the recording for the study started, each participant's comfortable walking speed with/out the device was determined. Participants then practiced the instructed tapping task on the given device while simultaneously stand/walked on the treadmill and maintained the device either at the abdomen or the shoulder position. In total, there were 80 trials, divided into 8 blocks. Each block had ten randomly arranged tapping and no-tapping tasks, and these eight blocks were randomly defined as one of the combinations of the arm height and the movement condition. This randomization prevented any learning and anticipatory effect exhibited by the participants. They were given several breaks throughout the experiment to prevent fatigue.

Data Analysis

Qualisys's QTM software was used to label the kinematic markers and cut the tapping task trial into two halves offline using the timeline control bar. Recorded trials containing kinematics and analog EMG data were exported as MAT files. These files were later analyzed using customized MATLAB scripts written in MATLAB (R2018b) to examine the kinematics and EMG data and understand the neuromotor control strategy formulated by our motor system for the hand and arm segments while doing three layers of motor tasks: Arm height, Tasks, and Movement conditions. Seven participants' data were excluded because either the participant's markers were not identified by the software during offline or EMG signals had some problem as some of the muscles had significant movement artifacts and/or did not record correctly.

Kinematic and EMG data were filtered and resampled using appropriate filters and algorithms, as described in the first study. Thumb local coordinates relative to the smartphone using the distal thumb marker along with three smartphone markers were computed. Figure 3.4 shows the kinematics of thumb, along with filtered and rectified EMG of three hand muscles of a participant performing a No-tap task (A) and multi-tap task as 'H‣QGMGQ‣H' (B) during standing and holding the device in the abdomen position.

The second study mainly examined the effect of the two arm heights in addition to the nature of the Task and Movement conditions. Thus, the reference values were saved using a MATLAB script for accounting for each tapping task, movement condition, and arm height maintained during each trial (Appendix M). The Start and End points of a trial from the thumb local kinematics, the number of the thumb keypresses on the touchscreen for a given task trial, and delete any extra erroneous taps were found out as described in the first study. A MATLAB script was written to find the mean muscular activity (mean EMG) between Start and End points

for all the recorded trials. Figure 3.4 shows the Start and End points represented by the green and red line respectively over the filtered and rectified EMGs of the hand muscles from which the mean EMG was calculated.

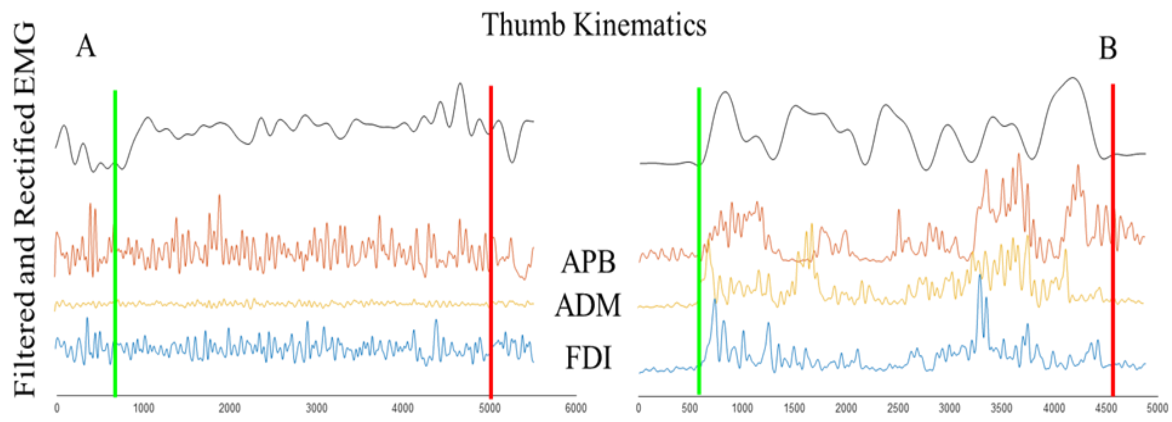


Figure 3.4. Thumb kinematics and Filtered and rectified EMGs of three hand muscles. A. Thumb kinematics during the no-tap task, standing and holding the device in Abdomen; B. Thumb kinematics during multi-tap-QGMGQ, standing and holding the device in Abdomen; Green and Red lines represent Start and End points respectively

The second study mainly examined the effect of the two arm heights on the muscular activity of the upper limb during smartphone manipulation tasks such as grasping (no-tap) and grasping (multi-tap) over different movement conditions. Shoulder and elbow joint angles were computed to understand the arm height effect. Markers placed on the greater trochanter, shoulder, and elbow and using the dot product, the shoulder angle between two vector arms: vector 1-greater trochanter and shoulder and vector 2: shoulder and elbow were calculated. Similarly, three markers: shoulder, elbow, and radial wrist were used to find two vector arms. One vector arm was defined by shoulder and elbow markers, while another vector arm was defined by the elbow and radial wrist marker. Both angles represented flexion and extension of the shoulder and elbow joints during a trial were calculated.

A slope of a line can be found by drawing a straight line between two points. In this study, the slope was calculated between the shoulder and MCPI markers (in the vertical/sagittal

plane), and the slope angle was defined as the inverse tangent of the slope where the slope between the shoulder and MCPI markers was calculated using a slope equation [slope=(y2-y1)/(x2-x1)]. In this study, when participants were instructed to perform a task (no-tap/tapping) and maintain a movement condition on the given device at the shoulder position, the slope angle would be small if the shoulder and MCPI markers are that same levels. However, if they had not maintained their MCPI marker at the shoulder marker level, say in the case of the abdomen, the slope angle would be automatically negative and greater in magnitude.

A z-coordinate ratio was calculated to identify whether the MCPI marker of the hand is at the shoulder or abdomen by creating a ratio of z-coordinate MCPI marker to z-coordinate shoulder marker. If the MCPI marker was held at/around the shoulder position assuming the MCPI and Shoulder markers are approximately at the same height from the ground, and at a comfortable distance, the z-coordinate ratio would be (approximately) equal to 1. However, if the device were held at the abdomen, the z-coordinate ratio would be less than to 1 as the z-value of the MCPI marker would be less than the z-value of the Shoulder marker. To understand this description, refer to figure 3.5, which shows the difference in the z-coordinate ratio between shoulder and abdomen position.

The coefficient of variation (COV) represented the relative positioning of Shoulder-MCPI (markers) variability in X, Y, Z direction. First, the relative distance between MCPI and the Shoulder marker was calculated by subtracting shoulder marker data from MCPI marker data between Start and End points. The mean and standard deviation of each trial between Start and End points was calculated, such that the relative standard deviation was divided by the relative mean to COV.

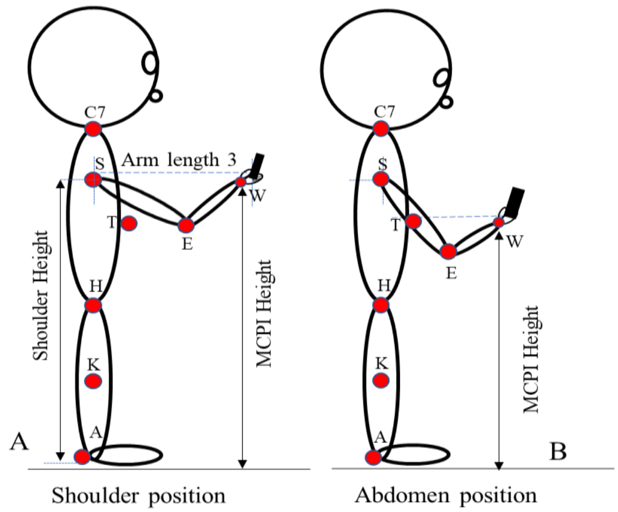


Figure 3.5. Z-coordinate ratio comparison between shoulder (A) and abdomen positions (B)

Dependent variables like shoulder and elbow joint, slope angles, z-coordinate ratio, and COV were also calculated between Start and End points and later averaged. Once the mean EMG of all the fourteen muscles along with mean elbow and shoulder angles, mean slope angle, mean z-coordinate ratio and mean COV for all the recorded trials were calculated for a subject from all the recorded trials, similar condition trials based upon the reference values were grouped and averaged. Graphs were plotted using Graphpad prism 8.

Experiment Design and Statistical Analysis

In this study, there are three independent variables: Movement condition (MCOND), Grasping with/out tapping task (Task), and Arm-position. Similarly, there are five dependent variables: mean EMG, shoulder, and elbow joint angles, slope angle, z-coordinate ratio, and COV. Using SPSS Statistics 26, a 4 (MCOND) x 5 (Task) x 2 (Arm-position) repeated-measures ANOVA was used to determine whether these three independent variables would have any effect on all the dependent variables: mean EMG, shoulder and elbow joint angles, slope angle, z-coordinate ratio and COV with p <0.05 criterion to test all the hypotheses. Post-hoc analysis with

a Bonferroni correction test was conducted if there was a significant effect. The summary of the experiment design is shown in table 3.3.

Table 3.3. Conditions to be tested

Arm heights	**MCOND**	**Nature**	**Task**	**Executed task**
Shoulder /Abdomen	Standing (W0)/ Slow walking (W80)/ Normal Walking (W100)/ Fastest Walking (W120)	Grasping with/out tapping	No-tap/ Multi-tap	Thumb rested at ‘H’/ H▸QGMGQ▸H▸PGZGP▸H

RESULTS

Mean EMG of Hand muscles

Results of repeated-measures ANOVA was shown in table 3.4. The mean and standard error values of MCOND x Arm of hand muscles were shown in Appendix N. Despite showing a significant effect of MCOND on mean EMG of FDI, the post-hoc tests with the Bonferroni correction (Figure 3.6 A) did not show any significant differences between standing and walking at a different percentage of CWSD. For ADM (Figure 3.6 A), walking at different % of CWSD increased mean EMG compared to standing ($p \leq 0.045$). For APB (Figure 3.6 A), it did not show any significant effect of MCOND on its mean EMG. There was a significant effect of arm heights on FDI muscle only (Figure 3.6 A). Post-hoc test with the Bonferroni correction (Figure 3.6 B) showed that the abdomen position resulted in a significantly higher mean EMG compared to the shoulder for FDI ($p=0.035$).

Table 3.4. ANOVA summary table on mean EMG of Hand muscles

mean EMG	Effects	(df1, df2)	F	p-value	ηp2
FDI	MCOND	2.614, 52.279	3.463	0.028	0.148
	Arm	1, 20	5.119	0.035	0.204
	Task	1.47, 29.407	30.888	0.000	0.607
	MCOND x Arm	3, 60	1.818	0.154	0.083
	MCOND x Task	2.886, 57.721	2.232	0.096	0.100
	Arm x Task	1.306, 26.110	3.095	0.081	0.134
	MCOND x Arm x Task	3.017, 60.335	1.544	0.212	0.072
APB	MCOND	3, 60	0.638	0.594	.031
	Arm	1, 20	0.962	0.338	.046
	Task	1.318, 26.366	5.528	0.019	0.217
	MCOND x Arm	3, 60	0.238	0.869	0.012
	MCOND x Task	2.964, 59.289	1.652	0.188	0.076
	Arm x Task	1.299, 25.986	0.033	0.910	0.002
	MCOND x Arm x Task	2.648, 52.955	0.577	0.612	0.028
ADI	MCOND	1.683, 33.662	4.770	0.020	0.193
	Arm	1, 20	1.600	0.220	0.074
	Task	1.097, 21.932	11.497	0.002	0.365
	MCOND x Arm	3, 60	0.780	0.510	0.038
	MCOND x Task	3.157, 63.138	0.876	0.463	0.042
	Arm x Task	1.454, 29.075	3.370	0.062	0.144
	MCOND x Arm x Task	3.923, 78.463	0.284	0.884	0.014

Mean EMG of Forearm muscles

Results of repeated-measures ANOVA was shown in table 3.5. The table also showed that there was a significant effect of MCOND x Arm on the mean EMG of ECU muscle (p=0.007). Figure 3.8 revealed that ECU muscle showed a distinct activation pattern for different levels of MCOND while manipulating smartphone device at shoulder compared to the abdomen position. The level of muscle activity increased from standing to walking (W80) while manipulating the smartphone at the abdomen to shoulder position. Further, the activity increased for the fastest walking (W120) while manipulating smartphone device at the shoulder from normal walking (W100) while manipulating smartphone device at the abdomen position. The

mean and standard error of MCOND x Arm of forearm muscles is shown in Appendix N. Post-hoc tests with Bonferroni correction for pairwise comparisons (Figure 3.7 A) revealed that For ECU and ED, walking at different % of CWSD increased mean EMG compared to standing ($p \leq 0.04$). For FCR, post hoc tests showed a higher mean EMG for the fastest walking compared to the Standing ($p=0.016$). Post-hoc test revealed (Figure 3.7 B) that when compared for the mean EMG of the two arm heights, FCR showed higher mean EMG for the abdomen compared to the shoulder ($p=0.008$). In contrast, the other three extrinsic muscles, ECU, EPL, and ED, showed higher mean EMG values for the shoulder compared to the abdomen ($p \leq 0.044$).

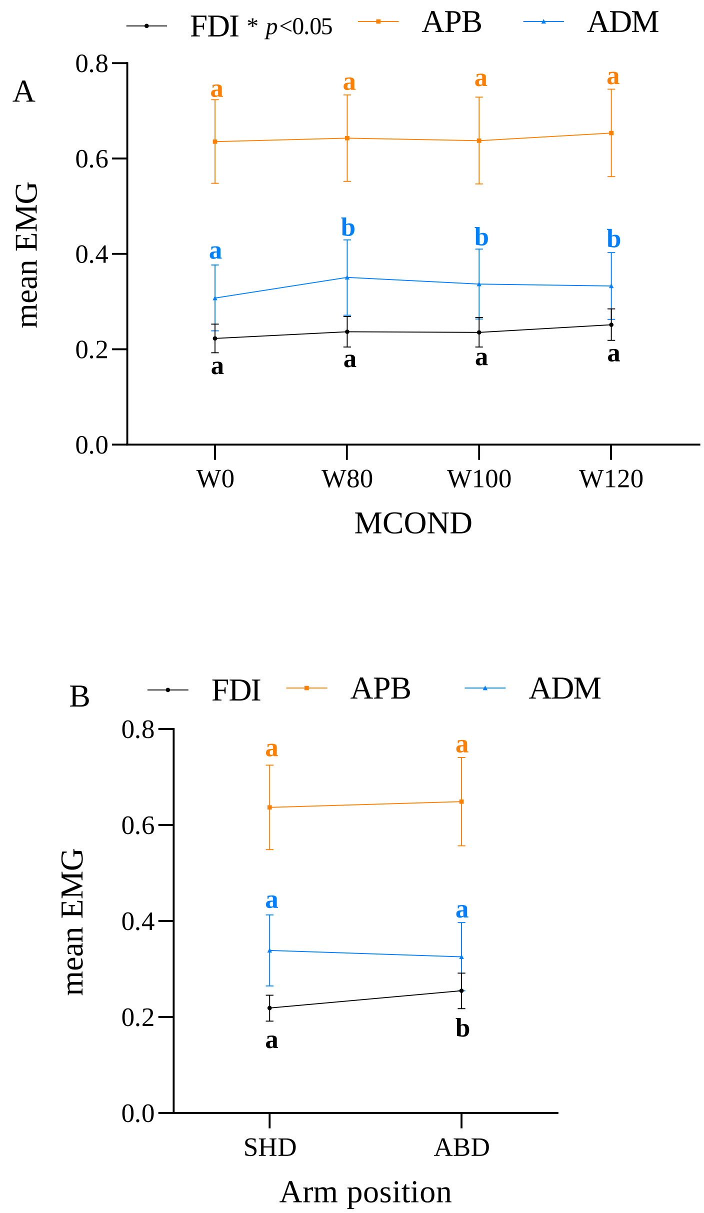


Figure 3.6. Effect of MCOND (A), and Arm (B) on mean EMG of Hand muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups (p<0.05)

Table 3.5. ANOVA summary table on mean EMG of Forearm muscles

mean EMG	Effects	(df1, df2)	F	p-value	ηp2
FCR	MCOND	1.648, 32.953	4.819	0.020	0.194
	Arm	1, 20	8.568	0.008	0.300
	Task	1.184, 23.677	19.641	0.000	0.495
	MCOND x Arm	3, 60	1.941	0.133	0.088
	MCOND x Task	3.055, 61.095	1.242	0.302	0.058
	Arm x Task	1.120, 22.397	0.425	0.543	0.021
	MCOND x Arm x Task	2.487, 49.738	0.263	0.815	0.013
ECU	MCOND	2.103, 42.050	13.327	0.000	0.40
	Arm	1, 20	40.224	0.000	0.668
	Task	1.093, 21.865	32.523	0.000	0.619
	MCOND x Arm	3, 60	4.473	0.007	0.183
	MCOND x Task	1.631, 32.614	0.656	0.496	0.032
	Arm x Task	1.326, 26.526	0.399	0.591	0.020
	MCOND x Arm x Task	6, 120	0.995	0.432	0.047
EPL	MCOND	2.085, 41.699	2.458	0.096	0.109
	Arm	1, 20	10.225	0.005	0.338
	Task	1.045, 20.891	21.613	0.000	0.519
	MCOND x Arm	3, 60	0.335	0.800	0.016
	MCOND x Task	3.090. 61.797	0.312	0.822	0.015
	Arm x Task	1.738, 34.757	0.499	0.586	0.024
	MCOND x Arm x Task	3.544, 70.88	0.419	0.772	0.021
ED	MCOND	2.039, 40.782	8.098	0.001	0.288
	Arm	1, 20	16.063	0.001	0.445
	Task	1.21, 24.203	27.016	0.000	0.575
	MCOND x Arm	1.668, 33.362	0.633	0.510	0.031
	MCOND x Task	1.597, 31.930	2.519	0.107	0.112
	Arm x Task	1.245, 24.897	0.334	0.617	0.016
	MCOND x Arm x Task	1.467, 29.339	0.845	0.407	0.041

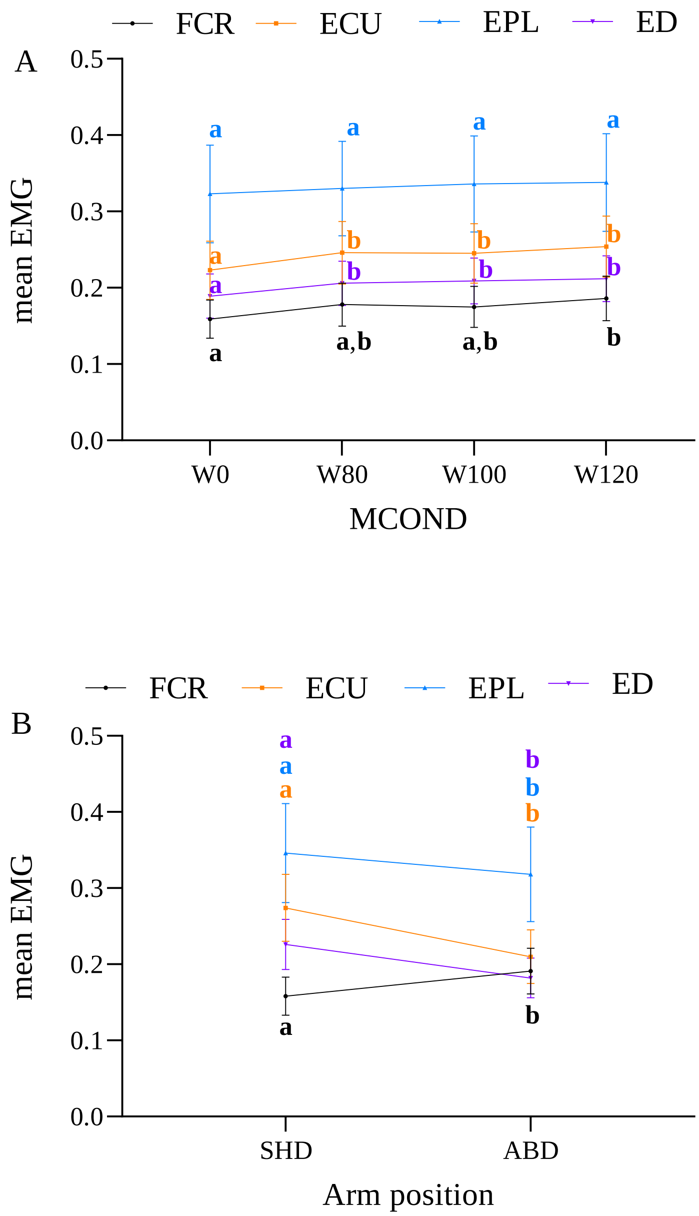


Figure 3.7. Effect of MCOND (A), and Arm (B) on mean EMG of Forearm muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups (p<0.05)

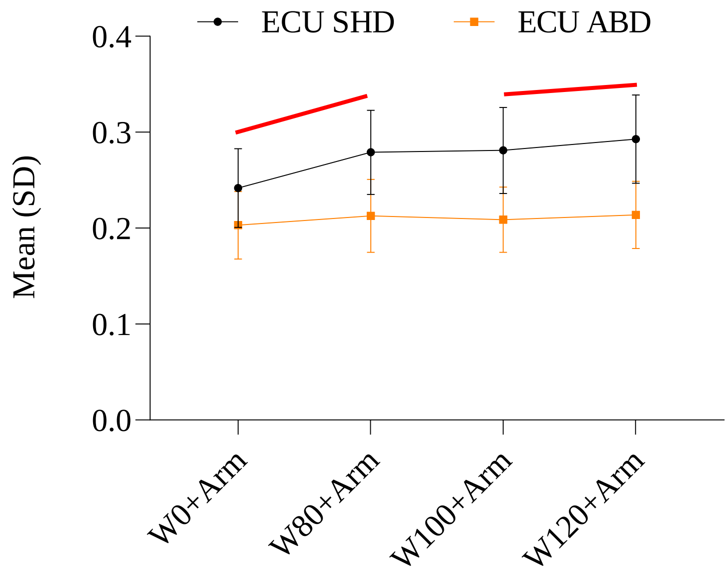


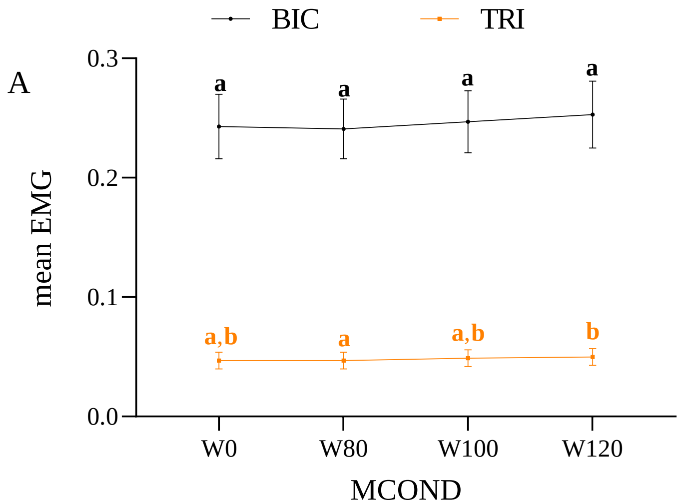
Figure 3.8. Effect of MCOND x Arm on mean EMG of ECU ($p<0.05$). Values are Mean ± SE.

Mean EMG of Upper arm muscles

Results of repeated-measures ANOVA was shown in table 3.6. There was a significant effect of MCOND x Arm on the mean EMG of TRI only ($p \leq 0.050$). Figure 3.10 shows that TRI showed a distinct activation pattern for different levels of MCOND while manipulating smartphone device at shoulder compared to the abdomen position. Interestingly, the level of muscle activity (of TRI) decreased from standing (W0) to slow walking (W80) at shoulder position compared to increased activity at the abdomen. However, the activity increased from slow (W80) to normal walking (W100) manipulating smartphone at shoulder position than compared to abdomen such the activity remained similar in the latter position. The mean and standard error values of MCOND x Arm of the upper arm were shown in Appendix N. Post-hoc test (Figure 3.9 A) showed that a higher mean EMG for the fastest walking compared to the slow walking for TRI ($p=0.026$). Post-hoc test (Figure 3.9 B) showed when compared for the mean EMG for the two arm heights, shoulder position resulted in higher mean EMG compared to the abdomen for both BIC and TRI ($p \leq 0.001$).

Table 3.6. ANOVA summary table on mean EMG of Upper arm muscles

mean EMG	**Effects**	**(df1, df2)**	**F**	**p-value**	**ηp2**
BIC	MCOND	3, 60	0.859	0.468	0.041
	Arm	1, 20	46.146	0.000	0.698
	Task	1.071, 21.418	3.370	0.078	0.144
	MCOND x Arm	1.899, 37.977	1.043	0.359	0.050
	MCOND x Task	2.026, 40.512	0.367	0.697	0.018
	Arm x Task	1.273, 25.465	2.048	0.162	0.093
	MCOND x Arm x Task	1.907, 38.144	3.278	0.051	0.141
TRI	MCOND	3, 60	4.358	0.008	0.179
	Arm	1, 20	29.296	0.000	0.594
	Task	1.127, 22.533	14.450	0.001	0.419
	MCOND x Arm	2.088, 41.75	3.183	0.050	0.137
	MCOND x Task	2.7, 53.994	1.715	0.179	0.079
	Arm x Task	1.132, 22.637	9.050	0.005	0.312
	MCOND x Arm x Task	2.601, 52.010	1.163	0.329	0.055



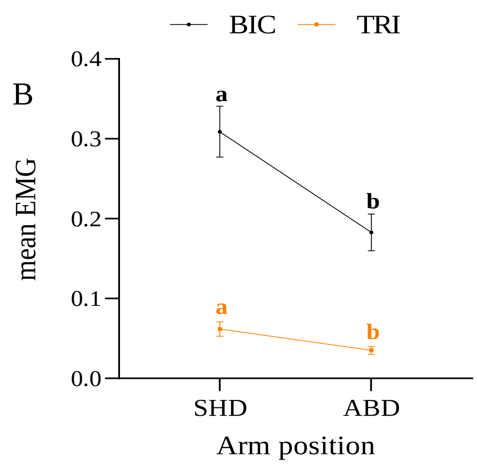


Figure 3.9. Effect of MCOND (A), and Arm (B) on mean EMG of Upper arm muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups (p<0.05)

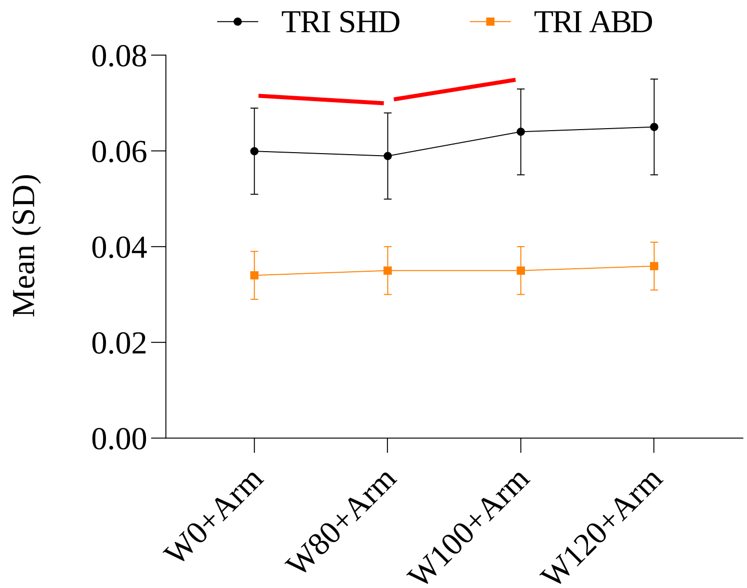


Figure 3.10. Effect of MCOND x Arm on mean EMG of TRI ($p<0.05$), Values are Mean ± SE

Mean EMG of Shoulder muscles

Results of repeated-measures ANOVA was shown in table 3.7. Table 3.7 showed that there was a significant effect of MCOND on mean EMG of ADEL; however, its post-hoc test (Figure 3.11 A) showed that there was a higher mean EMG value for the fastest walking compared to the Standing for ADEL and its p-value was 0.059, greater than $p=0.05$. Likewise, the post-hoc test (Figure 3.11 A) showed a higher mean EMG value for the fastest walking compared to the Standing for PDEL ($p=0.009$). Further, Post-hoc analysis (Figure 3.11 B), when compared for the mean EMG of the two arm heights, shoulder position resulted in higher mean EMG compared to the abdomen for ADEL, MDEL, and PDEL ($p\leq0.001$).

Table 3.7. ANOVA summary table on mean EMG of Shoulder muscles

mean EMG	**Effects**	**(df1, df2)**	**F**	**p-value**	**ηp2**
ADEL	MCOND	1.878, 37.558	4.751	0.016	0.192
	Arm	1, 20	82.164	0.000	0.804
	Task	1.058, 21.167	9.948	0.004	0.332
	MCOND x Arm	3, 60	1.731	0.170	0.080
	MCOND x Task	2.683, 53.658	3.101	0.039	0.134
	Arm x Task	1.078, 21.551	45.131	0.000	0.693
	MCOND x Arm x Task	2.627, 52.536	1.029	0.380	0.049
MDEL	MCOND	2.107, 42.145	1.802	0.176	0.083
	Arm	1, 20	22.067	0.000	0.525
	Task	1.076, 21.530	12.748	0.001	0.389
	MCOND x Arm	3, 60	1.294	0.285	0.061
	MCOND x Task	2.664, 53.279	1.387	0.258	0.065
	Arm x Task	1.094,21.870	13.565	0.001	0.404
	MCOND x Arm x Task	2.652, 53.037	2.685	0.062	0.118
PDEL	MCOND	3, 60	6.994	0.000	.259
	Arm	1, 20	45.890	0.000	0.696
	Task	1.056, 21.129	12.282	0.002	0.380
	MCOND x Arm	3, 60	1.893	0.140	0.086
	MCOND x Task	2.342, 46.84	1.043	0.370	0.050
	Arm x Task	1.180, 23.608	11.387	0.002	0.363
	MCOND x Arm x Task	2.249, 44.973	0.773	0.481	0.037

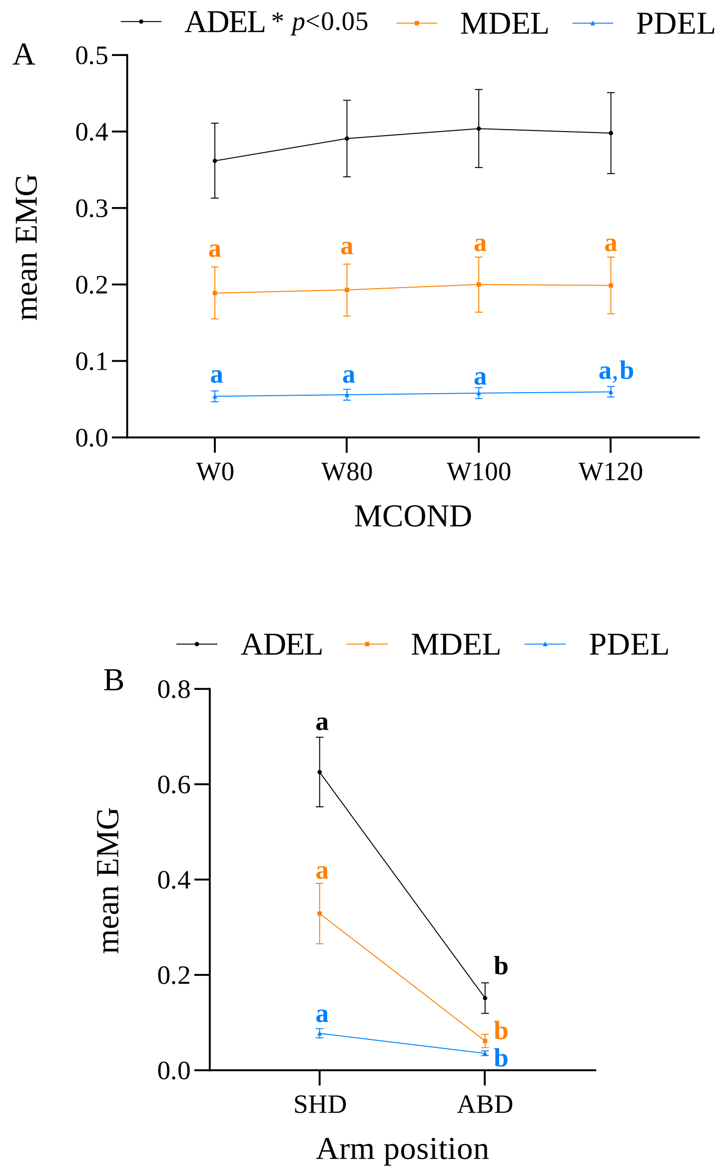


Figure 3.11. Effect of MCOND (A), and Arm (B) on mean EMG of Shoulder muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p<0.05$)

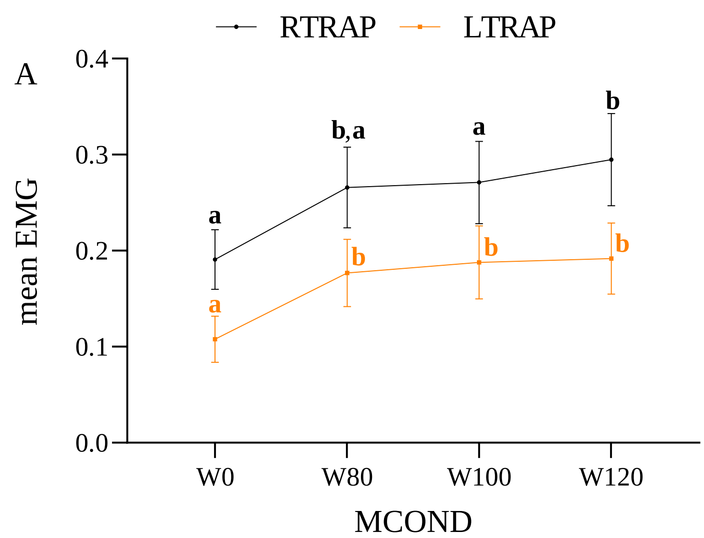
Mean EMG of Neck muscles

Results of repeated-measures ANOVA was shown in table 3.8. Post-hoc test showed (Figure 3.12 A) that there was a higher mean EMG value for the fastest walking and slow walking compared to the Standing for both RTRAP and LTRAP ($p\leq0.024$). In addition, it was

also found that the fastest walking resulted in higher mean EMG value for RTRAP compared to normal walking (*p*=0.046) while the normal walking resulted in significantly higher mean EMG value compared to the Standing (*p*=0.08) in case of LTRAP. Further, Post-hoc test (Figure 3.12 B), when compared for the mean EMG of the two arm heights, shoulder position resulted in higher mean EMG compared to the abdomen for RTRAP (*p*≤0.001) while abdomen resulted in higher mean EMG compared the shoulder for LTRAP muscle (*p*=0.018).

Table 3.8. ANOVA summary table on mean EMG of Neck muscles

mean EMG	**Effects**	**(df1, df2)**	**F**	**p-value**	**ηp2**
RTRAP	MCOND	1.238, 24.766	9.583	0.003	0.324
	Arm	1, 20	26.477	0.000	0.570
	Task	1.047, 20.934	0.295	0.603	0.015
	MCOND x Arm	2.132, 42.636	0.861	0.436	0.041
	MCOND x Task	2.29, 45.809	0.365	0.724	0.018
	Arm x Task	1.198, 23.964	9.223	0.004	0.316
	MCOND x Arm x Task	2, 39.994	2.261	0.117	0.102
LTRAP	MCOND	1.19, 23.802	10.955	0.002	0.354
	Arm	1, 20	6.626	0.018	0.249
	Task	1.077, 21.544	9.683	0.004	0.326
	MCOND x Arm	3, 60	0.471	0.704	0.023
	MCOND x Task	1.99, 39.975	1.445	0.248	0.067
	Arm x Task	1.055,21.096	4.692	0.040	0.190
	MCOND x Arm x Task	2.473, 49.459	0.500	0.649	0.024



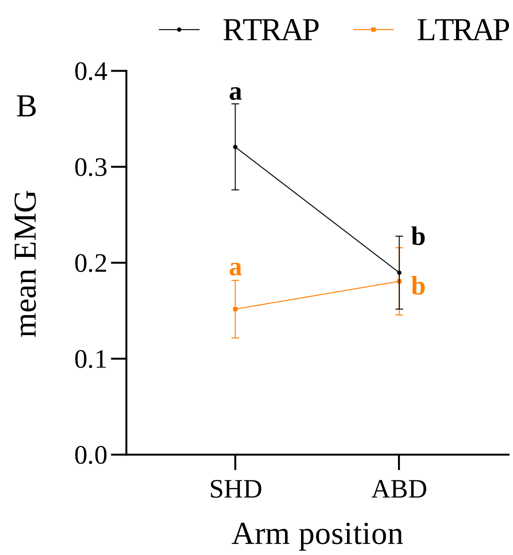


Figure 3.12. Effect of MCOND (A), and Arm (B) on mean EMG of Neck muscles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups ($p<0.05$)

Coefficient of Variation (COV)

Results of repeated-measures ANOVA was shown in table 3.9. Post-hoc analysis showed that there was a significantly lower variation during Standing compared to different levels of CWSD for x-coordinate (anterior-posterior direction) ($p \leq 0.001$). Arm height also had a

significant effect on the COV in the x-coordinate. Post-hoc test showed that there was higher variation at the abdomen level compared to the shoulder level for x-coordinate (anterior-posterior direction) (p=0.001).

Table 3.9. ANOVA summary on COV

COV	**Effects**	**(df1, df2)**	**F**	**p-value**	**ηp2**
cov_x	MCOND	3, 60	195.932	0.000	0.907
	Arm	1, 20	61.915	0.000	0.756
	Task	1.529, 30.572	21.738	0.000	0.521
	MCOND x Arm	3, 60	23.332	0.000	0.538
cov_y	MCOND	1.1776, 35.516	1.215	0.305	0.057
	Arm	1, 20	2.287	0.146	0.103
	Task	1.118, 22.361	3.195	0.084	0.138
	MCOND x Arm	1.745, 34.904	1.032	0.358	0.049
cov_z	MCOND	1.684, 33.678	1.126	0.328	0.053
	Arm	1, 20	1.903	0.183	0.087
	Task	1.424, 28.478	0.437	0.583	0.021
	MCOND x Arm	1.684, 33.688	1.166	0.316	0.055

Elbow, Shoulder and Slope angle

Results of repeated-measures ANOVA was shown in table 3.10. According to the Post-hoc test, standing resulted in a higher elbow angle compared to different levels of CWSD ($p \leq 0.001$). Post-hoc analysis, when compared for the elbow angle for two arm heights, shoulder position resulted in a greater elbow angle compared to the abdomen position ($p \leq 0.001$). For shoulder angle, Standing resulted in a lower shoulder angle compared to normal walking and fastest walking ($p \leq 0.027$). In addition, the post-hoc test showed that there was almost a significant difference in shoulder angle during standing and slow walking as p=0.053. When compared for the shoulder angle between two arm heights, the shoulder position resulted in a greater shoulder angle compared to the abdomen position ($p \leq 0.001$).

Table 3.10. ANOVA summary table on the angle

Angle	Effects	(df1, df2)	F	p-value	ηp2
Elbow angle	MCOND	3, 60	20.075	0.000	0.5010
	Arm	1, 20	17.755	0.000	0.47
	Task	1.082, 21.639	42.151	0.000	0.678
	MCOND x Arm	3, 60	1.284	0.288	0.06
	MCOND x Task	2.58, 51.604	12.66	0.000	0.388
	Arm x Task	1.104, 22.082	3.911	0.057	0.164
	MCOND x Arm x Task	1.698,33.961	0.576	0.540	0.028
Shoulder angle	MCOND	3, 60	6.724	0.001	0.252
	Arm	1, 20	602.402	0.000	0.968
	Task	1.189, 23.784	32.421	0.000	0.618
	MCOND x Arm	3, 60	3.158	0.031	0.136
	MCOND x Task	3.044, 60.882	2.725	0.051	0.12
	Arm x Task	2, 40	41.434	0.000	0.674
	MCOND x Arm x Task	2.452, 49.041	2.865	0.056	0.125
Slope angle	MCOND	3, 60	1.002	0.398	0.048
	Arm	1, 20	1096.83	0.000	0.982
	Task	1.365, 27.301	2.244	0.139	0.101
	MCOND x Arm	3, 60	0.871	0.461	0.042
	MCOND x Task	3.221, 64.413	2.777	0.045	0.122
	Arm x Task	1.432, 28.646	103.442	0.000	0.838
	MCOND x Arm x Task	2.571, 51.426	7.045	0.001	0.26

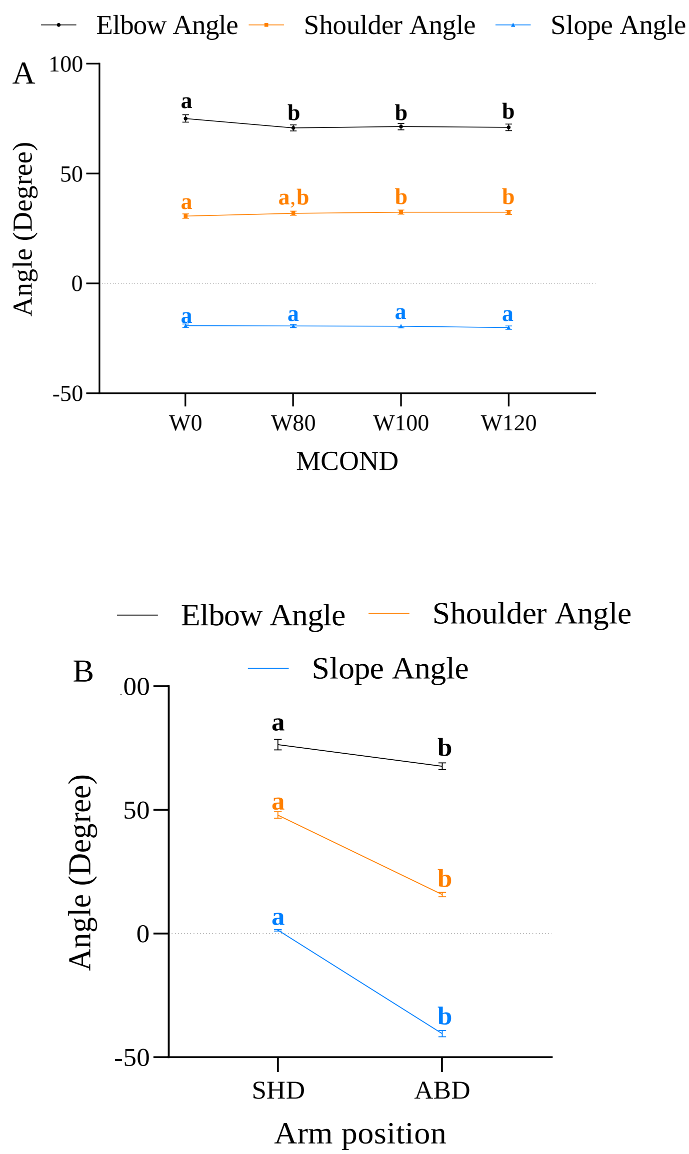


Figure 3.13. Effect of MCOND (A), and Arm (B) on Elbow, Shoulder, and Slope angles. Values are Mean ± SE. Different letters indicating significant differences between the groups while the same letters indicate no significant differences between the groups (p<0.05)

Z-coordinate ratio

Results of repeated-measures ANOVA was shown in table 3.11. According to the Post-hoc test, when compared for the z-coordinate ratio for two arm heights, smartphone manipulation at shoulder position resulted in a higher z-coordinate ratio compared to the abdomen position (p≤0.001).

Table 3.11. ANOVA summary table on the z-coordinate ratio

	Effects	**(df1, df2)**	**F**	**p-value**	**ηp2**
z-coordinate ratio	MCOND	1.987, 39.742	0.296	0.744	0.015
	Arm	1, 20	1033.26	0.000	0.981
	Task	1.388, 27.752	3.737	0.051	0.157
	MCOND x Arm	3, 60	2.15	0.103	0.097
	MCOND x Task	3.031, 60.628	3.055	0.035	0.132
	Arm x Task	1.428, 28.551	116.795	0.000	0.854
	MCOND x Arm x Task	2.76, 55.201	8.05	0.000	0.287

DISCUSSION

The second study was conducted to understand how different arm heights influence posture with respect to the shoulder and elbow joints, along with the muscular activity of the upper limb. These observations allowed further examination of the motor control strategies used to control hand and arm segments during smartphone manipulation under different movement conditions.

Effect of Arm height

We compared the muscle activity of the upper limb when smartphone manipulation occurred when the device was aligned to shoulder height and at the abdomen level during different movement conditions. The first and second hypotheses that muscle activity of arm (Hypothesis #1) and hand (Hypothesis #2) would be greater when the device was held at shoulder compared to the abdomen level was partially supported. A mixed effect of arm height on muscle activity of the upper limb was revealed except in two hand muscles (APB and ADM) as these two muscles did not show any significant difference with respect to arm position. FDI, FCR, and LTRAP muscles had significantly higher activity in the abdomen position. In contrast, ECU, EPL, ED, BIC, TRI, ADEL, MDEL, PDEL, and RTRAP muscles had significantly higher activity in the shoulder position.

When holding the device with the right hand for the shoulder position, we found that the right arm and hand were away, unsupported, and maintained at a certain height, which resulted in ~47° shoulder flexion and ~76° elbow extension. As a result, it increased the moment arm and, subsequently, the moment of inertia compared to the abdomen position (~15° shoulder flexion, ~67° elbow extension). This idea is consistent with previous studies as they concluded that the distance between the load and the body should be minimum when interacting, and as the distance

increases, the moment increases (Arborelius et al. 1986; Madinei and Ning 2018). It increased muscle activity in some arm and hand muscles, which could be used to overcome the external factors and help device interaction and support and stabilize the joints of the right arm and hand when held at the shoulder compared to the abdomen. The observed increase in muscle activity was consistent with previous studies as they concluded that compared to an object positioned closer to the body, working with an object placed at a distance requiring lifting to greater height would increase the muscle activities of the involved (and unsupported) limb (Habes et al. 1985; Cook and Kothiyal, 1998; Nielsen et al. 1998; Anton et al. 2001; Vandenberghe et al. 2010; Young et al. 2013; Kim et al. 2016; Kim et al. 2018). Further, this is consistent with the studies on seated smartphone studies where they demonstrated that manipulating smartphones at different heights with different typing styles such as one-handed versus two-handed typing and neck bent at different angles could significantly influence the muscle activity of the neck and upper extremity (Ko et al. 2016; Namwongsa et al. 2019).

Other studies demonstrated that smartphone users constantly tilted their head and neck forward to view the device screen during abdomen compared to shoulder position, which was associated with increased activation in the RTRAP and LTRAP muscles during abdomen rather than in shoulder position (Kushwah and Narvey 2018; Park et al. 2017; Syamala et al. 2018). In our study, increased activity of RTRAP muscle was observed in the shoulder position consistent with the need to support their right arm and hand to manipulate the device as it was held further away from the body at a higher height. At this position, proximal muscles like RTRAP and Deltoid muscles were activated to support the neck, shoulder, arm, and hand, including the weight of the smartphone, which was consistent with the finding of Bodin et al. (2019) and Zetterberg et al. (2013). On the other hand, LTRAP muscle exhibited significantly lower activity

for shoulder compared to the abdomen position, likely because it was not involved in supporting or raising the arm during smartphone manipulation at shoulder position.

FDI and FCR muscles both showed greater activation in the abdomen compared to the shoulder position, which was consistent with our previous result (study #1). In that study, although we did not specifically instruct participants to manipulate the device at the abdomen position, participants chose to manipulate the device at/around the abdomen region as their comfortable area. In that study, we found that both these muscles, FDI and FCR, were significantly active regardless of the tapping task or movement conditions. We suggested that FDI muscle activity tends to be increased for grasping and thumb motion purposes, which is consistent with previous studies (Bodin et al. 2019; Xiong and Muraki 2014) while FCR activity is increased to provide support against the gravity during smartphone manipulation (Dennerlein and Johnson 2006). When we move from the abdomen to the shoulder position, other muscles (ECU, EDP, and ED) got engaged to support the hand and forearm height and subsequently, smartphone manipulation.

Past studies related to smartphones have shown a mixed effect on APB and ADM muscles such that these muscles helped in one-handed thumb tapping (Kim et al. 2016; Kim et al. 2018; Xie et al. 2016) or in gripping (stabilizing) of a device by abducting little finger either from the bottom side or from the left side of the device (Ahn et al. 2016; Le et al. 2018). However, in this study, we found that the two muscles, APB and ADM, were not influenced by arm height. This difference could be because compared to others, our study specifically focused upon examining the effect of the arm height on the muscle activity of the upper limb involved in smartphone manipulation. So, regardless of arm height: shoulder or abdomen, these two muscle groups were required to maintain a constant muscle activation to assist in a constant grip of the

device and tapping of the device during smartphone manipulation. This result is consistent with the finding of Winges et al. (2007), who concluded that hand muscles were appropriately contracting, not only during grasping phase- for maintaining necessary stability but also during transportation involving both acceleration and deceleration phase of the object transport.

In short, the control strategy was significantly affected by the arm height as supported by the changes in muscle activity, barring some exceptions. We found there were significant changes in the joint angles of the shoulder and elbow angles with respect to the arm heights that were consistent with the changes in the magnitude of activation observed in the recorded muscles.

Effect of MCOND and Arm height

Our third hypothesis stated that walking would result in greater muscular activation patterns across the hand and arm muscles compared to standing when the device is held at the shoulder compared to the abdomen. It was expected that walking would result in more significant perturbation of the arm and the device at the shoulder position; thus, increased activation of the arm and hand muscles would be used to prevent instability of the arm and device. Based upon our result, we reject this hypothesis as there was an absence of significant interaction effects of arm height and MCOND for twelve muscles out of fourteen recorded muscles. The interaction effect of MCOND and arm height was significant for ECU and TRI muscles. Although the trends in each muscle were different, for both ECU and TRI, the shoulder position appeared to be more affected when comparing different levels of MCOND. In the ECU muscle, there was a ~15 % increase in muscle activity from standing to slow walking for the shoulder position and only a ~5% increase in muscle activity from standing to slow walking for the abdomen position. Similarly, in the TRI muscle, there was a ~8 % increase in muscle activity

from slow to normal walking for the shoulder position and no change from slow to normal walking for the abdomen position. As a result, for these two muscles, the effect of walking on muscle activity was more pronounced for the shoulder position compared to the abdomen.

In this study, we expected that manipulating a smartphone at an abdomen versus shoulder position would result in different activity in the muscles of the upper limb. Likewise, we expected different joint angles of the upper limb between the abdomen and shoulder position. Our study result supports such a hypothesis with some exceptions. For example, arm height had a significant effect on all the muscle activity of the upper limb except the APB, and ADM muscles such that ECU, EPL, ED, BIC, TRI, ADEL, MDEL, PDEL, and RTRAP muscles increased while FDI, FCR, and LTRAP muscles decreased for shoulder compared to abdomen position. These changes in the muscle activity due to the arm height were supported by changes in the joint angles of the upper limb. For instance, elbow extension and shoulder flexion were greater for the shoulder compared to the abdomen position. Increased muscle activity would help to stabilize the device and the arm as they are experiencing movement perturbation generated from the walking or gravitational pull due to unsupported limb. The observed increase in muscle activity was consistent with previous studies as they concluded that compared to an object positioned closer to the body, working with an object placed at a distance requiring lifting to greater height would increase the muscle activities of the involved (and unsupported) limb (Habes et al. 1985; Cook and Kothiyal, 1998; Nielsen et al. 1998; Anton et al. 2001; Vandenberghe et al. 2010; Young et al. 2013; Kim et al. 2016; Kim et al. 2018).

Similarly, we expected that manipulating a smartphone during standing versus walking at a different percentage of CWSD would result in different muscular activation patterns in the muscles of the upper limb. And our result again verified this assumption, where we saw that

there was a main effect of the movement condition (MCOND) affected all the muscle activity of the upper limb except the APB, EPL, BIC, and MDEL. However, there was a mixed effect when different levels of (increasing speed of) MCOND were analyzed for muscle activity of the upper limb. This muscle activation result (in Study #2) was inconsistent with study #1. In study #1, we found that the MCOND had significantly influenced all the muscular activity of the upper limb. Lack of consistency in the muscle activity between studies could have been due to differences in the device holding position for manipulation. Unlike in study # 1, where participants held the device in a comfortable position that tended to be at/around the abdomen position without further instruction, in Study 2, participants were specifically instructed to hold the device either at the shoulder or abdomen position. Increased in the muscle activity of the upper limb except for APB, EPL, BIC, and MDEL helps to dampen the arm movement against the inertial forces acting on the hand and arm due to walking and preventing instability of the smartphone (Gysin et al. 2003; von Werder and Disselhorst-Klug 2016). Increased in the muscle activity in the distal segment further improve the device grip and avoid the device instability generated from the thumb tapping (Eardley et al. 2018; Gustafsson et al. 2011).

Further, the joint angles showed a mixed effect for different levels of MCOND. That is, the elbow extension angle was greater during standing compared to walking while the shoulder flexion angle was greater for walking compared to standing. When walking started, participants adjusted their elbow position to raise the device and bring it closer to the body when they faced motion perturbation apart from gravitational pull due to walking. This adjustment at the elbow joint increased with walking speed from standing. This action of bringing the upper limb closer to their body would also reduce the moment arm and, subsequently, the torque that is generated from the inertial forces generated from walking. These inertial forces, acting in a downward

direction, can cause instability and movement in the unsupported upper limb. The increase in shoulder flexion during walking may be indicative of a compensatory strategy to prevent the hand from lowering too much, thus moving the smartphone outside of the instructed position.

With these individual effects of MCOND and arm height has such a profound effect, we assumed that there would be a combined effect of them on the muscle activity of the upper limb along with the joint angles when the smartphone was manipulated. However, our result showed that such interaction was not significant for most of the recorded muscles except ECU and TRI muscles. It could be suggested that both factors (MCOND and arm height) did not necessarily bring a compounded effect on the muscle activity of the upper limb when manipulating smartphone at one level (i.e., standing and holding at abdomen) vs. another level (walking at 120% of CWSD and holding at the shoulder). Our neuromuscular system was diligent enough to detect changes in the MCOND and arm height during smartphone manipulation. It did not necessarily 'ratchet up' the muscle loading of the upper limb. Instead, it would adopt a simple motor control strategy that would accommodate changes in the muscle activity of the upper limb according to the changes in the levels of the MCOND and arm height combined to accomplish smartphone manipulation. However, this accommodation in the muscle activity was not significant except for ECU and TRI muscles, which showed differences between levels (standing and holding at abdomen vs. walking at 120% of CWSD and holding at the shoulder).

Overall, a lack of significant interaction between these two independent variables (MCOND and arm height) is a useful control strategy implemented by our neuromuscular system. Such a control strategy prevents the neuromuscular system from the unnecessary increase in the gain of the muscle activity of the upper limb. Instead, the neuromuscular system intelligently generates a simple and efficient motor control strategy that would activate the

muscles of the upper limb to a sufficient amount to accomplish these multi-layered motor tasks related to the smartphone manipulation involving – grasping with/out tapping, movement condition, and maintain arm height without overloading (or unwanted gain).

CHAPTER 4. CONCLUSIONS

Smartphone manipulation is a unique example of object manipulation because it involves several layers of motor tasks executed simultaneously. For instance, it involves constant grasping of the device with the fingers and palm, followed by thumb tapping. Further, hand involved in thumb tapping are supported continuously by the arm, which is unsupported. Both hand and arm are continually under the influence of gravity and walking perturbation. With this study, we have examined the multi-muscle activation patterns of the upper limb along with the motor control strategy generated by our neuromuscular system that is needed during smartphone manipulation. Thus, the primary goal of this study was to understand the multi-muscle activation pattern for the upper limb during different movement conditions, grasping with/out tapping and arm heights and to understand the motor control strategy generated by the neuromuscular system.

KEY RESULTS

In study 1 (Chapter 2), we examined the multi-muscle activation pattern of the upper limb during a segment of the trial executed with a handheld smartphone device while maintaining different movement conditions, i.e., standing and walking at a different percentage of CWSD. We found that the activity in all recorded muscles increased with different levels of the movement conditions, while the pattern of change concerning segment differed among the muscles. With this result, we concluded that our neuromuscular system must maintain a distinctive muscle activation pattern (concurrently to activate a group of muscles of) in the proximal and distal segments that would allow us to achieve all the multi-layered motor tasks simultaneously.

In study 2 (Chapter 3), we examined the muscle loading generated when smartphones are manipulated at two comfortable arm heights: shoulder and abdomen by recording the muscle

activity of the upper limb during movement and tapping conditions. We found that there was an effect of arm height on the muscle activity of the upper limb as some muscles showed greater activation for the shoulder while some showed greater activation for the abdomen. With this result, we concluded that the arm height had a significant effect on the multi-muscle activation pattern. Additionally, we also found that the interaction between arm height and MCOND did not necessarily result in significant changes in the majority of the muscles. We thus concluded that the neuromuscular system would generate a ‘simple motor control strategy’ specifying the necessary muscle activity to accomplish smartphone manipulation.

STUDY ONE AND TWO COMBINED

We defined hand-smartphone manipulation as an example of hand-object manipulation. However, this task combines several tasks investigated separately in past studies, because, interaction with a smartphone requires a complex coordination of different motor skills. For instance, hand-smartphone manipulation involves more than just grasping with/out tapping; it also requires arm stabilization (as it is unsupported) either at abdomen or shoulder position. In addition, during performance of the task gravity pulls the arm downward while motion perturbation due to movement of the body and legs during gait perturbs the arm as well.. The two studies combined suggest, using surface electromyography recordings from fourteen different muscles of the upper limb, that our neuromuscular system accomplishes hand-smartphone manipulation under different conditions, including different arm heights, using a simple motor control strategy for the upper limb.

SUMMARY

Smartphone manipulation is an example of complex hand-object manipulation. Several studies have examined hand interaction with the various objects that are common in our daily

living or activities. With these two studies, we have tried to add one more piece of information about hand interacting with the smartphone as the later has become one of the prevalent objects in the 21st century. Since its discovery, these handheld devices have gone through a series of changes in their design and technology, enabling mankind to do several tasks using it. That's why its users are growing every year. Presently there are more than four billion people currently using these devices for several hours. With these studies, we have tried to understand what it takes for our neuromuscular system to control and manipulate these devices while fulfilling certain tasks such as grasping with/out tapping while maintaining upper arm coordination across different movement conditions and arm height.

FUTURE DIRECTIONS

Smartphones have become one of the ubiquitous tools of our daily living. Each year, companies are producing advanced handheld devices using better technological advancements that are available. As a result, smartphones have now become an amalgamation of several devices like computers, cameras, iPods, phones, etc., allowing us to do several tasks such as phone calls, send/receive text messages, emails, browse internet, photography, etc. However, most of the currently available smartphone devices are bigger and are not suitable for one-handed smartphone manipulation. Thus, for future studies, it would be interesting to examine the two-handed smartphone manipulation and its effect on the hand, forearm, arm, shoulder, and neck muscles.

Another exciting avenue for future research could be comparing the difference between multi-muscle activation patterns between texting and swiping as most of us nowadays swipe to check their social-networking websites. Lastly, there have not been many studies that have

defined postural and muscular synergies related to the upper limb during smartphone manipulation while executing different smartphone's cellular tasks and maintaining different movement conditions.

LIMITATION

There were a few limitations while conducting these two studies. One of them was the handheld mobile device used for both studies. Although most of the participants owned and used a smartphone device, they were using the experimental device for the first time. As a result, they took some time for them to learn to interact with the device, which could potentially influence muscle activity while recording. Participants were given ample time to get used to the device to limit this issue.

Most studies related to the smartphone are based upon the thumb interaction with the screen. In both studies, we did not pay attention to the placement of the index finger at the rear/back end of the device, as the literature suggests that such information could have helped us to understand the FDI activation during smartphone manipulation.

There were more female participants compared to male participants, restricting any comparison between male and female participants. Although our study did not focus on such comparison between male and female and their muscle activation, this could potentially be the reason for the differences that would most likely be linked to hand size.

APPENDIX A. IRB APPROVAL FORM

ACTION ON PROTOCOL APPROVAL REQUEST

LSU
Institutional Review Board
Dr. Dennis Landin, Chair
130 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
F: 225.578.5983
irb@lsu.edu
lsu.edu/research

TO: Arend Van Gemmert
Kinesiology

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: December 14, 2018

RE: **IRB#** 4170

TITLE: Kinematics and muscle activity during smartphone manipulation

New Protocol/Modification/Continuation: New Protocol

Review type: Full ____ Expedited _X_ **Review date:** 12/13/2018

Risk Factor: Minimal ___X___ Uncertain ______ Greater Than Minimal_______

Approved_____X_____ **Disapproved**__________

Approval Date: 12/14/2018 **Approval Expiration Date:** 12/13/2019

Re-review frequency: (annual unless otherwise stated)

Number of subjects approved: 50

LSU Proposal Number (if applicable):

By: Dennis Landin, Chairman _____DLandin_____

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –
Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. **SPECIAL NOTE: When emailing more than one recipient, make sure you use bcc.**

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb*

APPENDIX B. CONSENT FORMS

STUDY 1:
CONSENT TO PARTICIPATE IN A RESEARCH STUDY
INFORMED CONSENT

1. **Study Title:** Kinematics and muscle activity during smartphone manipulation
2. **Performance Site:** School of Kinesiology laboratories, Biomechanics Laboratory (Gym Armory, B-2), Louisiana State University and A&M College
3. **Investigators:** The following investigators are available for questions about the study:
   1) Dr. Arend W. A. Gemmert (Phone: 225-578-9142, Email: gemmert@lsu.edu)
   2) Dr. Nikita Kuznetsov (Phone: 225-578-3845, Email: nikita@lsu.edu)
   3) Dr. Sara A. Winges (Phone: 970-351-1956, Email: sara.winges@unco.edu)
4. **Purpose of the Study:** To better understand the complexity of multi-muscle patterns and the kinematics of the upper limb involved in smartphone manipulation.
5. **Participant Inclusion:** Young healthy adults (males and females) ages 18 to 40 years old with normal or corrected to normal vision.
6. **Participant Exclusion:** Excluded are individuals who are pregnant, have any orthopedic, cardiovascular, and/or neuromuscular health problems.
6. **Number of Participants:** 50.
7. **Study Procedures and Equipment:** You will complete several questionnaires for categorizing purposes. Furthermore, some measurements of your hands and upper limb dimensions will be taken. After these questionnaires, the surface of your skin will be cleaned with an alcohol swab, and surface electromyography electrodes will be attached to the surface of your arm, hand, and neck. Several reflective markers will be taped (medical tape to help prevent skin reactions) over segments of the upper and lower limbs and the trunk to monitor body movements.
   You will perform several trials of basic cellular tasks on the given smartphone device. These tasks include tapping different letters while standing and walking on a treadmill. First, you will be asked to walk at your comfortable walking speed (CWS) with the device on the treadmill. Then you are asked to watch the screen and walk once the PI starts the treadmill. The PI will slowly increase the speed of the treadmill until you indicate you have reached your comfortable walking speed. During the experiment, you will also be asked to walk at 80 and 120% of your comfortable walking speed. During the experiment, we will measure the kinematics and EMG signals, as also your performance on the tasks. The entire experiment will last approximately 3 hours.
8. **Benefits:** As a volunteer from the university community, you may earn extra credit for research participation. Otherwise, there are no other direct benefits for you.
9. **Risks/Discomforts:** No risks beyond risks associated with the regular use of smartphones in daily life are foreseen, except that tape may cause some skin irritation, which will be minimized with the use of medical tape. Performance during the experiment may result in some degree of fatigue, which would be mediated by providing sufficient rest periods. Every effort will be made to maintain the confidentiality of your records. Files will be kept in secure cabinets to which only the investigators have access.
10. **Right to Refuse:** You may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which you otherwise might be entitled.

11. **Privacy:** The LSU Institutional Review Board (which oversees university research with human participants) may inspect and/or copy the study records. The results of the study may be published, but no names or identifying information will be included in the publication. Other than as set forth above, subject identity will remain confidential unless disclosure is legally compelled.
12. **Signatures:** The study has been discussed with me, and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about Participants' rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the investigator's obligation to provide me with a signed copy of the consent form.

Subject Signature: ________________________________ Date: __________________

STUDY 2:

CONSENT TO PARTICIPATE IN A RESEARCH STUDY

INFORMED CONSENT

1. **Study Title:** Kinematics and muscle activity during smartphone manipulation
2. **Performance Site:** School of Kinesiology laboratories, Biomechanics Laboratory (Gym Armory, B-2), Louisiana State University and A&M College
3. **Investigators:** The following investigators are available for questions about the study:
   1) Prasanna Acharya (Phone: 856-426-1186, Email: pachar4@lsu.edu)
   2) Dr. Arend W. A. Van Gemmert (Phone: 225-578-9142, Email:gemmert@lsu.edu)
   3) Dr. Nikita Kuznetsov (Phone: 225-578-3845, Email: nikita@lsu.edu)
   4) Dr. Sara A. Winges (Phone: 970-351-1956, Email: sara.winges@unco.edu)
4. **Purpose of the Study:** To better understand the complexity of multi-muscle patterns and the kinematics of the upper limb involved in smartphone manipulation.
5. **Participant Inclusion:** Young healthy adults (males and females) ages 18 to 40 years old with normal or corrected to normal vision.
6. **Participant Exclusion:** Excluded are individuals who are pregnant, have any orthopedic, cardiovascular, and/or neuromuscular health problems.

6\. **Number of Participants:** 100.

7\. **Study Procedures and Equipment:** You will complete several questionnaires for categorizing purposes. Furthermore, some measurements of your hands and upper limbs will be taken. After the questionnaires and measurements, the surface of your skin will be cleaned with an alcohol swab. Then surface electromyography electrodes will be attached to the surface of your arm, hand, and neck. Also, several reflective markers will be taped (medical tape to help prevent skin reactions) on the upper and lower limbs and the trunk to monitor body movements. You will perform several trials of some basic cellular tasks on the smartphone handed to you. These tasks include tapping different letters while standing and walking on a treadmill and maintaining a two-arm height: either at the shoulder or abdomen level. The investigator will first determine your comfortable walking speed (CWS). A trial starts with you holding the device and standing on the treadmill. The investigator then will inform you that he is about to start and increase the speed of the treadmill. With each increment of the speed, he will ask you whether you have reached your comfortable walking speed with the device in your hand. Once you have reached your comfortable speed and walked for a few seconds, the researcher will ask you whether the treadmill can be stopped, after which the treadmill is slowed down and eventually stops. To increase your safety, you will be connected to the safety key of the treadmill to ensure that the treadmill immediately stops, or you can immediately stop the treadmill if an emergency occurs. If you feel that you lose balance, you can use the handrails for support. In addition, to minimize the risk of falling and/or losing your balance, a helper will stand right behind for support and will catch you if falling to prevent injury. You can take breaks between trials whenever you desire. During the experiment, you will be asked to maintain arm height either at the shoulder or abdomen level while simultaneously maintain standing and walking conditions at your comfortable speed, at 80%, and 120% of your comfortable walking speed. While you perform the tasks, we record kinematic and EMG signals. The entire experiment will last approximately 3 hours.

8\. **Benefits:** As a volunteer from the university community, you may earn extra credit for research participation. Otherwise, there are no other direct benefits for you.

9. **Risks/Discomforts:** No risks beyond risks associated with the regular use of smartphones in daily life are foreseen, except that tape may cause some skin irritation, which will be minimized with the use of medical tape. Performance during the experiment may result in some degree of fatigue, which would be mediated by providing sufficient rest periods. Every effort will be made to maintain the confidentiality of your records. Files will be kept in secure cabinets to which only the investigators have access.
10. **Right to Refuse:** You may choose not to participate or to withdraw from the study at any time without penalty or loss of any benefit to which you otherwise might be entitled.
11. **Privacy:** The LSU Institutional Review Board (which oversees university research with human participants) may inspect and/or copy the study records. The results of the study may be published, but no names or identifying information will be included in the publication. Other than as set forth above, subject identity will remain confidential unless disclosure is legally compelled.
12. **Signatures:** The study has been discussed with me, and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about Participants' rights or other concerns, I can contact Dennis Landin, Institutional Review Board, (225) 578-8692, irb@lsu.edu, www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the investigator's obligation to provide me with a signed copy of the consent form.

Subject Signature: ________________________________ Date: __________________

APPENDIX C. PHYSICAL EXAMINATION TESTS

Participants were evaluated for the Finkelstein test to confirm whether they have any current irritation or pain due to swelling of tendons around the base of the thumb. This irritation or swelling could be caused due to overuse of the thumb and its muscles due to thumb tapping for texting and other cellular application usages in their daily living, causing de-Quervain's tenosynovitis. Studies have shown that there is a direct association between prolific high-speed texting and pain and weakness at the base of the thumb/wrist, such that those individuals had a positive Finkelstein test and subsequent diagnosis of de Quervain's tenosynovitis (Ali et al. 2014). To do this test, these students would be asked to bend their thumb down across the palm and cover it (the thumb) with the fingers. After folding their fingers over the thumb, they have to make ulnar deviation (bend their wrist); if they feel pain while doing this action, it is likely being suggested that s/he has a positive de-Quervain's tenosynovitis. However, none of the participants showed any positive signs for the test, indicating they were not currently experiencing any pain related to texting with the thumb.

Participants were examined for the Phalen's (wrist flexion) test to determine whether these participants have any severity in their carpal tunnel and medial nerve in the wrist due to excessive smartphone usages (Lee et al. 2012). In the Phalen's tests, participants are required to place their elbows flexed and allowed the wrist into the maximum flexion. They have to maintain this position for 60 seconds. If they experience any tingling or abnormal sensations after 60 seconds, it is a positive sign of this test, indicating they could have carpal tunnel syndrome caused by the pressure on the median nerve. All twenty-four participants showed a negative sign for the test, meaning they were not currently experiencing any pain related to the wrist.

APPENDIX D. STUDY 1: PARTICIPANTS DEMOGRAPHICS DETAILS

Table D.1. Demographics Details (Study 1)

Subject ID (Txt)	Gender	Age (yrs)	Mass (Kg)	Height (m)	CWSD	CWS	Corrected vision	Handedness Test	
								Score	Interpretation
13	F	20	57	1.60	1.80	1.84	+0.75	20	Ambi
15	F	21	57	1.57	2.95	2.88	Yes	100	Right
16	F	21	64	1.65	2.99	2.52	No	100	Right
17	M	22	82	1.72	2.88	2.88	No	20	Ambi
18	M	22	N/A	1.85	3.60	2.88	No	73.3	Right
23	M	21	91	1.80	2.52	2.88	No	62.5	Right
25	F	20	N/A	1.65	2.52	2.70	R=-4.50; L= -4.25*	100	Right
26	F	19	68	1.67	2.52	2.70	+1	73.3	Right
30	F	21	49	1.57	2.81	2.70	Yes	100	Right
31	F	22	59	1.65	2.52	2.88	No	62.5	Right
32	F	20	N/A	1.57	2.16	2.34	Yes	71.5	Right
33	F	22	64	1.57	2.88	2.88	R=-1.25; L=-1.00	100	Right
35	M	21	N/A	1.68	1.98	2.30	No	100	Right
36	F	22	N/A	1.60	2.34	3.06	R=-0.5; L=-0.5	73.3	Right
37	M	22	68	1.80	1.80	2.16	No	90	Right
38	M	22	68	1.78	2.16	2.34	No	60	Right
39	M	22	79	1.83	2.88	3.24	No	70	Right
40	F	21	N/A	1.67	2.52	2.99	No	50	Right
41	F	20	60	1.62	2.88	3.28	No	-83.3	Left
42	F	20	N/A	1.72	2.52	2.88	Yes	76.4	Right
43	M	22	73	1.85	2.88	2.88	No	100	Right
44	F	20	N/A	1.65	2.70	3.06	No	80	Right
46	F	20	57	1.60	2.45	2.70	No	100	Right
47	F	20	62	1.58	1.98	2.52	No	44.4	Right

Note: M= Male; F= Female; CWSD= Comfortable walking speed with device (kmph); CWS= Comfortable walking speed(kmph); Txt25 had astigmatism in left eye* ; Ambi= Ambidextrous

APPENDIX E. STUDY 1: HAND AND ARM MEASUREMENTS IN CM

Table E.1. Hand and Arm Measurement (Study 1)

Subject ID (Txt)	HL	PL	DH	Max HB	TL	PB	TC	SL
13	17.5	10	8	9.5	5.8	11	5.8	71
15	17.8	10.1	7.8	10	5.9	11	4.6	68
16	18	10.5	8.6	10.7	5.8	11.5	5.2	69
17	18.5	11	8.9	12.5	6.2	13	5.54	76.5
18	20	12	9	12	7	13.2	5.4	77.5
23	19.5	11.7	10	12	6.4	12	5.6	76.2
25	18	10	8	8.5	6	10	6	70
26	17	10	8.4	11	5.6	11.5	5.8	68.5
30	17.5	10.1	7.4	9.1	5.6	10	5	68.4
31	18.1	10.5	7.7	9.4	5.7	9.8	5.7	70.5
32	16.8	10	7.1	8.4	5.3	8.9	5.5	67
33	19.7	11	8.1	9.7	6	9.8	5.5	77
35	18.5	11.1	7.5	9.2	6.1	10	5.9	69.4
36	17	9.7	8.1	9.7	5.2	11.2	5.3	67
37	20.2	11.5	8.7	12.2	6.5	12.5	6	77
38	18	11	9	11	6	13	6	75
39	19	11	9	11	7.5	12	6	78
40	18.2	10.6	8.4	9.8	5.8	10	5.4	69.8
41	17.5	10.4	7.5	8.6	5.7	9.4	5.6	67.3
42	18.9	10.6	7.2	9	6.5	9.4	5.3	72.1
43	19.5	11.6	8.4	11.8	6.6	11.7	6.1	79.5
44	16.9	10	7.7	8.3	5.5	8.7	5.5	67
46	16.3	9	7.6	8.7	5.5	9.4	5.2	68
47	17	10	7.7	8.9	5.9	9.4	5.4	67

Definition

1. Hand length (HL): The base of the hand to the top of the middle finger measured along the long axis of the hand
2. Palm length (PL): The distance between the root of the palm and root of the middle finger
3. Distal handbreadth (DH): The breadth of the hand as measured across the distal end of the metacarpal bones (Cakit et al. 2014)
4. Maximum handbreadth (Max HB): The breadth of the hand measured at the level of the maximum bulge of the palm including thumb (Mohammad 2005)
5. Thumb length (TL): The distance between the second joint of the thumb to the tip of the thumb
6. Palm breadth (PB): Distal ends of the first and fifth metacarpals
7. Thumb circumference (TC): The widest point of the thumb
8. Arm Length 1 (SL): The peak of the shoulder and the distal end of the middle finger

APPENDIX F. STUDY 2: PARTICIPANTS DEMOGRAPHICS DETAILS

Table F.1. Demographics details (Study 2)

Subject ID (Tx)	Gender	Age (yrs)	Mass (Kg)	Height (m)	CWSD	CWS	Corrected vision	Handedness Test	
								Score	Interpretation
5	F	20	46.58	1.64	1.80	2.16	Yes	100	Right
7	M	21	64.74	1.79	2.41	2.70	No	100	Right
9	F	21	76.18	1.69	2.70	3.06	Yes	82.3	Right
10	F	21	61.02	1.76	2.38	3.06	Yes	90	Right
11	F	21	70.46	1.70	2.52	3.60	Yes	100	Right
12	F	23	72.46	1.70	1.80	2.34	No	100	Right
13	F	21	64.29	1.64	2.34	2.88	No	90	Right
14	F	22	63.92	1.64	2.88	4.32	Yes	44.4	Right
15	F	21	49.12	1.57	2.34	2.81	20/30+G	100	Right
16	F	21	71.10	1.71	2.16	2.38	No	70	Right
17	M	21	63.11	1.76	2.56	3.17	Yes	88.8	Right
18	M	21	78.72	1.76	2.34	2.70	Yes	73.3	Right
19	F	20	113.32	1.68	2.02	2.52	No	28.5	Ambi
20	M	20	73.37	1.71	2.34	2.66	No	100	Right
21	F	20	63.65	1.63	2.34	2.70	Yes	20	Ambi
22	F	20	71.82	1.68	1.98	2.34	Yes	83.3	Right
24	F	21	60.11	1.56	2.88	4.32	No	100	Right
25	M	22	96.16	1.88	2.70	3.06	No	33.3	Ambi
26	F	22	66.37	1.71	2.88	3.24	No	15.8	Ambi
27	F	21	59.11	1.65	2.70	3.24	No	25.9	Ambi
28	F	20	53.94	1.63	2.34	3.24	No	100	Right

Note: G= glasses; Ambi= Ambidextrous

APPENDIX G. STUDY 2: HAND AND ARM MEASUREMENTS IN CM

Table G.1. Hand and Arm Measurement (Study 2)

Subject ID (Tx)	HL	PL	DH	Max HB	TL	PB	TC	SL	AL1	AL2
5	17.8	10.5	7.5	8.5	6	9	4.5	77	66	49.2
7	19	11	8.9	10.7	6.4	12	5.3	75	64	52.3
9	18.2	10.2	8.5	10	6	11	5	70.5	60	46
10	18.3	10.1	7.7	9.4	6.5	10	4.5	74.2	64.2	41.36
11	17.4	10	7.4	8.9	5.7	9.3	4.5	71	59.7	43.66
12	18.1	10.5	7.9	10	6.2	10.6	5.5	74	62	46.7
13	17.6	10	8.2	9.8	5.6	10.8	4.9	68.4	58	49.67
14	17.5	10	8	9.5	6.3	10.7	5	74.6	63	47.9
15	16.1	9.3	7.5	9.4	5.7	10.2	5	68.5	60	41.3
16	18	10.1	8.5	10.2	6	11.5	6	74.1	64	44.5
17	17.2	9.5	8.7	10.5	5.7	11.5	55.5	74.2	63.5	49.9
18	18.5	10.5	8.7	10.7	6.7	11.5	5.3	76.5	65.6	40.8
19	17.3	10	9.8	10.5	6.4	11.3	5.5	70.7	58.7	49.86
20	17.7	10.2	7.7	10.4	6.5	11.5	5.4	72.9	63.1	50.1
21	17.4	9.7	7.9	10.1	5.9	10.8	5	66.7	57	40.4
22	17.7	9.9	8.1	10.1	5.9	11.3	5.7	72	62.1	47.4
24	16.9	9.4	7.7	9.4	5.7	11.1	5.6	65.5	56.3	40
25	19.7	11	9.8	11.4	6.9	13.8	6	80.5	68.1	54.6
26	17.3	9.9	8.4	9.8	6.1	10.9	5.7	70.7	60.5	52.4
27	17.7	10.2	8.9	9.8	5.9	10.6	5.7	74.2	64.4	47.4
28	16.1	9.3	7.7	9.4	5.6	10.2	5.1	66.1	58.5	36.9

Definition

1. Arm length 2 (AL2): The distance between the acromion of the shoulder to the MCP of the index finger (MCPI) such that the arm and the wrist were kept neutral while the fingers were folded (made a fist), helping to identify the crease of the MCPI.
2. Arm length 3 (AL3): The distance between the acromion of the shoulder to the MCPI such that this distance was measured when the arm was slightly flexed, as shown in figure 3.1 (C), making this distance smaller than the first arm length.

APPENDIX H. ONLINE QUESTIONNAIRE

1. Do you own a cellphone or a smartphone?
2. How long have you been using a cell/smartphone?
3. What model do you currently use (or name of the cell/smartphone)?
4. How long have you been using the current cell/smartphone?
5. Did you own a cell/smartphone before the current device(s)?
6. What was the brand of the previously owned cell/smartphone?
7. The orientation of the device while using it for texting, browsing, chatting, etc.?
8. Any discomfort at the base of the thumb joint or wrist after using your device for a while?
9. When do you often use your device in a day regardless of the application?
10. Most preferred mode of communication with your friends
11. What is the most preferred mode of communication with your family members?
12. Where do you use your cell/smartphone every day?
13. Commonly used application(s) on your cell/smartphone?
14. Time spends on the device.
15. Average Text/day, email sent, hours spent on talking (voice/video calls), Hours spent on games, YouTube watched, listen to music, browsing the internet for news, banking, uber, booking tickets, etc., social networking sites like Facebook, Photos from the device
16. Device Grasp
17. Tapping/Gesture/Others
18. Comfortable using devices while walking, standing, and sitting?
19. Preferred Grasp style while walking, standing, and sitting?

APPENDIX I. EDINBURGH HANDEDNESS INVENTORY TEST

Edinburgh Handedness Inventory[1]

Participant ID:____________ Date: _ _ /_ _ / _ _ _ _

Please indicate with a one (1) your preference in using your left or right hand in the following tasks. Where the preference is so strong you would never use the other hand, unless absolutely forced to, put a two (2). If you are indifferent, put a one in each column (1 | 1). Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

Please stop here

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97-113.

Save and email the completed form to a.rawlings@uq.edu.au

APPENDIX J. MUSCLES, EMG PREAMPLIFIERS, AND TESTING MANEUVERS

Table J.1. Muscles, EMG Preamplifiers and Testing methods

Ch#	Region	Muscles	EMG Amplifier	Muscle Test
1	Hand	First Dorsal Interosseous (FDI)	MA-422 and GS26 Pre-gelled Disposable sEMG Electrodes	Abduct index finger
2		Abductor Pollicis Brevis (APB)		Moves (abducts) thumb across the palm (Oppose thumb across the palm, extend downwards)
3		Abductor Digiti Minimi (ADM)		Abducts little finger
4	Forearm	Flexor Carpi Radialis (FCR)	MA-411	Radial dev./Flexion and abduction at the wrist
5		Extensor Carpi Ulnaris (ECU)		Extension and adduction at the wrist
6		Extensor Pollicis Longus (EPL)		Extend thumb up and back (Extension of the wrist)
7		Extensor Digitorum (ED)		Extends medial four digits at metacarpophalangeal joints or extends a hand at wrist joint
8	Upper arm	Biceps Brachii (BIC)	MA-422 and Neuroplus EMG disposable medical gel electrode (A10040-5)	Flex at elbow
9		Triceps Brachii (TRI)		Extend at elbow
10	Shoulder	Anterior Deltoid (ADEL)		Flexion and internal rotation/Forward elevation of the arm.
11		Medial Deltoid (MDEL)		Abduct arm
12		Posterior Deltoid (PDEL)		Extension and lateral rotation
13, 14	Neck	Right and Left Trapezius (RTRAP & LTRAP)		Squeeze shoulder blades together

APPENDIX K. STUDY 1: MARKER PLACEMENT ON THE HUMAN BODY

Table K.1. Marker placement on the human body (Study 1)

Marker #	Anatomical Landmarks	Markers abbreviation	Marker size (mm)
1, 2	Right and Left of front Temple (Head)	RHEAD & LHEAD	25.4
3	Dorsal side of the head (Backhead)	BHEAD	
4	7th Cervical vertebrae (Spinous process of the 7th cervical vertebrae)	C7	
5, 6	Right and Left of Acromio-clavicular joint (Shoulder)	RSHO & LSHO	
7, 8	Right and Left of lateral epicondyle of the humerus (elbow)	RELB & LELB	
9, 10	Right and Left of Femur Greater trochanter	RGT & LGT	
11	Right Thigh (medial ½ of the Femur)	RTH	
12, 13	Right and Left of Lateral epicondyle of the femur (knee)	RKNE & LKNE	
14, 15	Right and Left of Lateral malleolus (ankle)	RANK & LANK	
16, 17	Right and Left of Calcaneous of the foot (Heel)	RHEEL & LHEEL	
18, 19	Styloid process of the right radius and ulnar (lateral and medial side of the right wrist)	RLW & RMW	
20, 21	Styloid process of the left radius and ulnar (lateral and medial side of the left wrist)	LLW & LMW	
22, 23	Right dorsal aspect of the ulnar (medial) and radius (lateral) (forearm)	FOR_R & FOR_L	
24, 25	Distal phalange and Interphalangeal (IP) of the thumb	DTH & IPTH	9.5
26, 27	Metacarpophalangeal (MCP) and Carpometacarpal (CMC) of the thumb	MCPTH & CMCTH	
28, 29	Metacarpophalangeal (MCP) of second (index) and fifth (little) digit	MCPI & MCPL	
30, 31	Carpometacarpal (CMC) of (index) and fifth (little) digit	CMCI & CMCL	
32	Bottom left phone (on edge)	BLPH	
33, 34	Top left and Top right phone (on edge)	TLPH A& TRPH	

APPENDIX L. STUDY 2: MARKER PLACEMENT ON THE HUMAN BODY

Table L.1. Marker placement on the human body (Study 2)

Marker#	Anatomical Landmarks	Markers abbreviation	Marker size (mm)
1, 2	Right and Left Ear (Tragus)	REAR & LEAR	9.5
3, 4	Right and Left Eye (Canthus)	REYE & LEYE	
5	Glabella (part of the forehead above and between the eyebrows)	GLAB	
6	7th Cervical vertebrae	C7	25.4
7, 8	Right and Left of Acromio-clavicular joint (Shoulder)	RSHO & LSHO	
9, 10	Manubrium and Xiphoid process of the sternum	MANU & XIPH	
11, 12	Right and Left of lateral epicondyle of the humerus (elbow)	RELB & LELB	
13, 14	Right and Left of Femur Greater trochanter	RGT & LGT	
15	Right Thigh (medial ½ of the Femur)	RTH	
16, 17	Right and Left of Lateral epicondyle of the femur (knee)	RKNE & LKNE	
18, 19	Right and Left of Lateral malleolus (ankle)	RANK & LANK	
20, 21	Right and Left of Calcaneous of the foot (Heel)	RHEEL & LHEEL	
22, 23	Styloid process of the right radius and ulnar (lateral and medial side of the right wrist)	RLW & RMW	9.5
24, 25	Styloid process of the left radius and ulnar (lateral and medial side of the left wrist)	LLW & LMW	
26, 27	Right dorsal aspect of the ulnar (medial) and radius (lateral) (forearm)	FOR_R & FOR_L	
28, 29	Distal phalange and Interphalangeal (IP) of the thumb	DTH & IPTH	
30, 31	Metacarpophalangeal (MCP) and Carpometacarpal (CMC) of the thumb	MCPTH & CMCTH	
32, 33	Metacarpophalangeal (MCP) of second (index) and fifth (little) digit	MCPI & MCPL	
34, 35	Carpometacarpal (CMC) of (index) and fifth (little) digit	CMCI & CMCL	
36, 37, 38	Bottom left, Top left and Top right phone (on edge)	BLPH, TLPH & TRPH	

APPENDIX M. CONDITIONS AND ITS REFERENCE VALUES

Table M.1. Conditions and reference values (Study 1)

MCOND	Task	Task-direction	MCOND	Task	Task-direction
0	0	0	100	0	0
0	1	1	100	1	1
0	1	2	100	1	2
0	2	1	100	2	1
0	2	2	100	2	2
80	0	0	120	0	0
80	1	1	120	1	1
80	1	2	120	1	2
80	2	1	120	2	1
80	2	2	120	2	2

1. Task: 0= No-tap; 1=Single-tap; 2= Multi-tap
2. Task-direction: 0= = No-tap (No-direction); 1= Left to Right (QGMGQ); 2= Right to Left (PGZGP);

Table M.2. Conditions and reference values (Study 2)

MCOND	Arm height	Task	Task-direction	MCOND	Arm height	Task	Task-direction
0	1	0	0	0	1	0	0
0	1	1	1	0	1	1	1
0	1	1	2	0	1	1	2
0	2	0	0	0	2	0	0
0	2	1	1	0	2	1	1
0	2	1	2	0	2	1	2
80	1	0	0	80	1	0	0
80	1	1	1	80	1	1	1
80	1	1	2	80	1	1	2
80	2	0	0	80	2	0	0
80	2	1	1	80	2	1	1
80	2	1	2	80	2	1	2

1. MCONDs:0= Standing; 80= Slow walking; 100= Normal Walking; 120= Fastest Walking;
2. Task: 0= No-tap; 1= Multi-tap;
3. Task-direction: 0= = No-tap (No-direction); 1= Left to Right (QGMGQ); 2= Right to Left (PGZGP);
4. Arm height: 1= Shoulder; 2= Abdomen

APPENDIX N. STUDY 2: MEAN AND STANDARD ERROR FOR MCOND x ARM

Table N.1. Mean and standard error of Hand muscles

Label	FDI (MCOND*Arm *p*>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.200	0.027	W0+ABD	0.247	0.035
W80+SHD	0.224	0.030	W80+ABD	0.249	0.035
W100+SHD	0.210	0.025	W100+ABD	0.261	0.040
W120+SHD	0.242	0.032	W120+ABD	0.262	0.038
Label	APB (MCOND*Arm *p*>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.630	0.085	W0+ABD	0.641	0.092
W80+SHD	0.635	0.088	W80+ABD	0.652	0.094
W100+SHD	0.627	0.091	W100+ABD	0.650	0.091
W120+SHD	0.654	0.092	W120+ABD	0.654	0.093
Label	ADM (MCOND*Arm *p*>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.312	0.067	W0+ABD	0.305	0.071
W80+SHD	0.367	0.082	W80+ABD	0.334	0.077
W100+SHD	0.337	0.077	W100+ABD	0.338	0.070
W120+SHD	0.340	0.072	W120+ABD	0.326	0.069

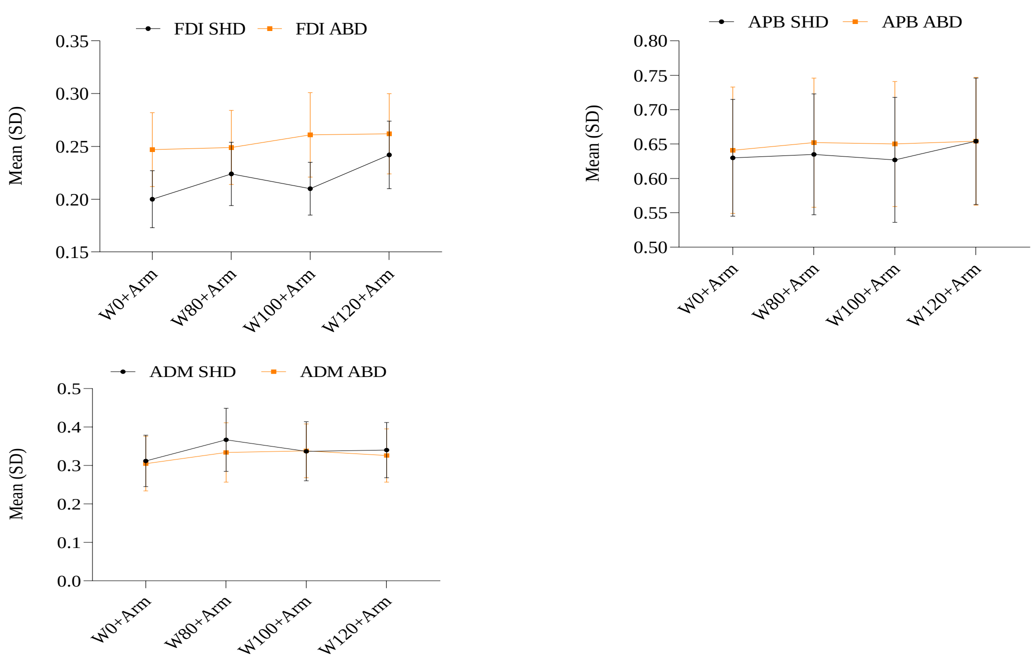


Figure N.1. Effect of MCOND x Arm on mean EMG of Hand muscles

Table N.2. Mean and standard error of Forearm muscles

Label	FCR (MCOND*Arm *p*>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.137	0.022	W0+ABD	0.182	0.030
W80+SHD	0.162	0.025	W80+ABD	0.193	0.032
W100+SHD	0.159	0.026	W100+ABD	0.192	0.029
W120+SHD	0.174	0.028	W120+ABD	0.198	0.031
Label	EPL (MCOND*Arm *p*>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.336	0.066	W0+ABD	0.309	0.063
W80+SHD	0.345	0.064	W80+ABD	0.316	0.061
W100+SHD	0.347	0.064	W100+ABD	0.324	0.062
W120+SHD	0.355	0.067	W120+ABD	0.322	0.061
Label	ED				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.210	0.033	W0+ABD	0.169	0.025
W80+SHD	0.226	0.033	W80+ABD	0.186	0.026
W100+SHD	0.231	0.033	W100+ABD	0.187	0.027
W120+SHD	0.238	0.036	W120+ABD	0.187	0.026
Label	ECU (MCOND*Arm *p*=0.007)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.242	0.041	W0+ABD	0.203	0.035
W80+SHD	0.279	0.044	W80+ABD	0.213	0.038
W100+SHD	0.281	0.045	W100+ABD	0.209	0.034
W120+SHD	0.293	0.046	W120+ABD	0.214	0.035

Table N.3. Mean and standard error of Upper arm and Shoulder muscles

Label	BIC (MCOND*Arm p>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.300	0.033	W0+ABD	0.187	0.028
W80+SHD	0.302	0.03	W80+ABD	0.180	0.022
W100+SHD	0.311	0.033	W100+ABD	0.184	0.023
W120+SHD	0.322	0.034	W120+ABD	0.183	0.023
Label	TRI (MCOND*Arm p=0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.060	0.009	W0+ABD	0.034	0.005
W80+SHD	0.059	0.009	W80+ABD	0.035	0.005
W100+SHD	0.064	0.009	W100+ABD	0.035	0.005
W120+SHD	0.065	0.010	W120+ABD	0.036	0.005
Label	ADEL (MCOND*Arm p>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.589	0.071	W0+ABD	0.135	0.034
W80+SHD	0.622	0.071	W80+ABD	0.159	0.033
W100+SHD	0.651	0.076	W100+ABD	0.157	0.032
W120+SHD	0.640	0.079	W120+ABD	0.157	0.033
Label	MDEL (MCOND*Arm p>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.324	0.062	W0+ABD	0.053	0.012
W80+SHD	0.320	0.060	W80+ABD	0.065	0.015
W100+SHD	0.338	0.064	W100+ABD	0.063	0.013
W120+SHD	0.333	0.066	W120+ABD	0.065	0.015
Label	PDEL (MCOND*Arm p>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.075	0.010	W0+ABD	0.032	0.004
W80+SHD	0.075	0.009	W80+ABD	0.037	0.005
W100+SHD	0.080	0.009	W100+ABD	0.037	0.004
W120+SHD	0.081	0.010	W120+ABD	0.038	0.005

Table N.4. Mean and standard error of Neck muscles

Label	RTRAP (MCOND*Arm *p*>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.254	0.038	W0+ABD	0.128	0.031
W80+SHD	0.323	0.046	W80+ABD	0.209	0.042
W100+SHD	0.345	0.052	W100+ABD	0.196	0.039
W120+SHD	0.361	0.054	W120+ABD	0.229	0.046
Label	LTRAP (MCOND*Arm *p*>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	0.091	0.020	W0+ABD	0.125	0.029
W80+SHD	0.159	0.033	W80+ABD	0.195	0.039
W100+SHD	0.178	0.037	W100+ABD	0.198	0.040
W120+SHD	0.180	0.037	W120+ABD	0.204	0.037

Table N.5. Mean and standard error of Angles

Label	Elbow (MCOND*Arm *p*>0.05)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	80.057	2.237	W0+ABD	70.095	1.703
W80+SHD	74.433	1.937	W80+ABD	67.273	1.642
W100+SHD	76.043	2.322	W100+ABD	66.712	1.345
W120+SHD	75.285	2.33	W120+ABD	66.749	1.328
Label	Shoulder (MCOND*Arm *p*=0.031)				
MCOND+SHD	**MEAN**	**SD**	**MCOND+ABD**	**MEAN**	**SE**
W0+SHD	46.248	1.345	W0+ABD	15.131	0.965
W80+SHD	47.696	1.446	W80+ABD	16.245	0.877
W100+SHD	49.19	1.486	W100+ABD	15.783	0.838
W120+SHD	48.767	1.297	W120+ABD	16.047	0.907

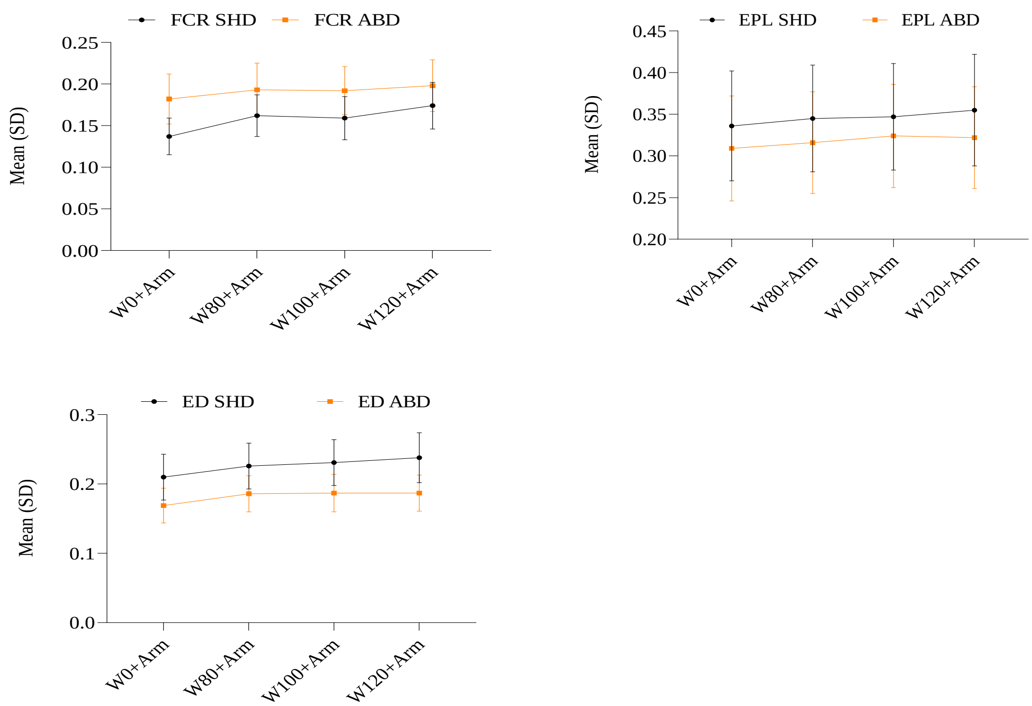


Figure N.2. Effect of MCOND x Arm on mean EMG of Forearm muscles

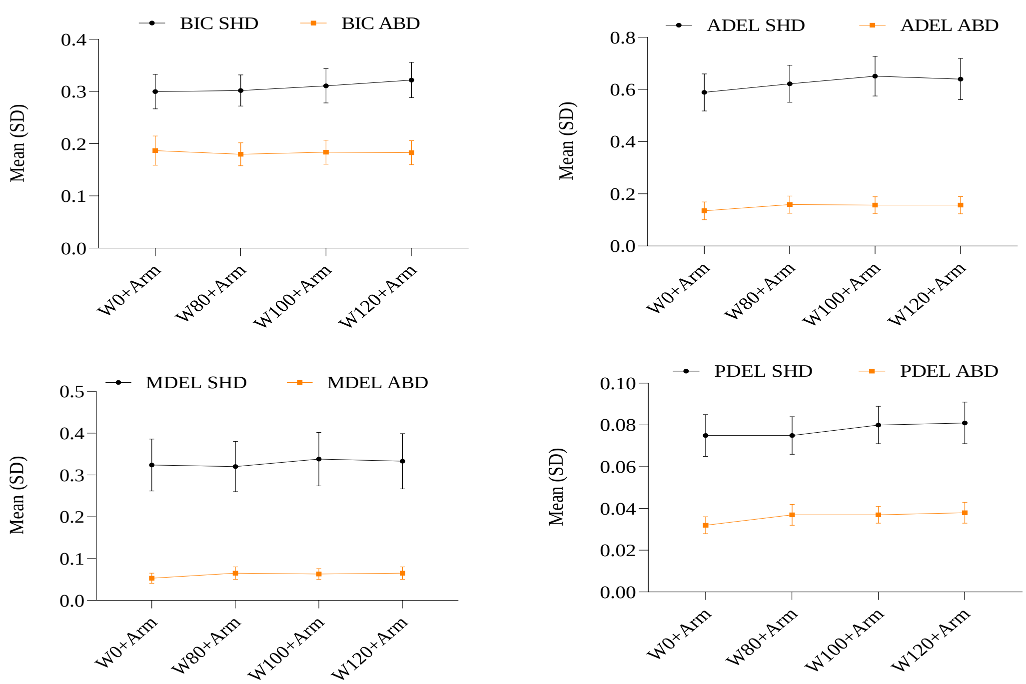


Figure N.3. Effect of MCOND x Arm on mean EMG of the Upper arm and Shoulder muscles

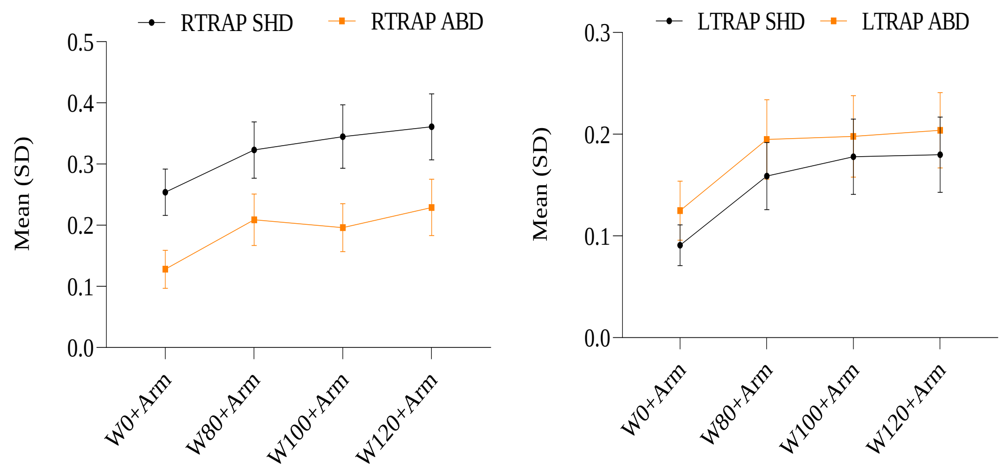


Figure N.4. Effect of MCOND x Arm on mean EMG of Neck muscles

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