Investigating Thumb Mechanics in Texting Using Novel Instrumentation Methods

by

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Abstract

As text messaging becomes a primary form of communication, risk of pathophysiological consequences rises. Evaluating thumb mechanics during one and two-handed texting, may increase understanding of how texting methods influence parameters such as texting forces and muscle activity. Comparing texting between normally limbed and people with limb loss may highlight the influence of previously existing musculoskeletal symptoms.

A unique instrumentation method was created to capture thumb forces on a cell phone screen. Myoelectric signals were recorded while an 8-camera Vicon M-Cam system was utilized to capture the motions of texting.

Results indicated that females had larger texting impulse and net joint torques than males, possibly due to hand size, which was also found to have an effect on phone stability; as phone size increased in relation to the person's hand, the phone positioning became more unstable. Thumb speed and duration of muscle activity were both significantly higher for one-handed texting. Increased pain, coupled with significantly slower texting rates and modified posture for people with limb loss, suggest more presence of previously existing musculoskeletal symptoms.

One–handed texting increases the concern for increased musculoskeletal injuries, especially for people with limb loss.

Key words: texting, kinematics, RSI, postures, forces, motion capture

Dedication

For the best of friends, my Mom and Aunt Joe.

Acknowledgments

Completing this project would not have been possible without the support of my supervisors. Their belief in me to not only take me on as their student, but also their support has allowed me to grow and develop integral skills that I will value and test throughout my career.

The success of this project is greatly credited to the staff and students at the Institute of Biomedical Engineering. Their willingness to help me overcome many road blocks throughout this project, particularly John Hayden, whose kindness and intelligence kept the Vicon system alive, just long enough.

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Abbreviations

- ADL – Activities of daily living
- AP - Adductor pollicis
- APB - Abductor pollicis brevis
- APL - Abductor pollicis longus
- ASIS – Anterior superior iliac spine
- CMC - Carpometacarpal
- CWTA – Canadian Wireless Telecommunications Association
- DAQ – Data acquisition
- DOF – Degrees of freedom
- ECRB – Extensor carpi radialis brevis
- ECRL – Extensor carpi radialis longus
- ED - Extensor digitorum
- EMG –Electromyography
- EPB - Extensor pollicis brevis
- EPL - Extensor pollicis longus
- FDI - First dorsal interosseous
- FPB - Flexor pollicis brevis
- FPL - Flexor pollicis longus
- GCS – Global coordinate system
- GUI – Graphic user interface
- IBME – Institute of Biomedical Engineering
- IP – Interphalangeal
- LCS – Local coordinate system
- MCP – Metacarpophalangeal
- MRI – Magnetic resonance imaging
- MVC – Maximum voluntary contraction
- OP - Oppenens pollicis
- RSI – Repetitive strain injury
- WCB – Worker's compensation board

Introduction

1.1 Motivation

As mobile phone use increases and text messaging becomes a primary form of communication, concern for the pathophysiological consequences of excessive texting arises. The Canadian Wireless Telecommunications Association (CWTA) reported that in 2014, Canadians sent a total of 186 billion text messages, approximately 510 million per day (Hardy, 2013). Moreover, mobile data traffic, including other forms of data messaging, is predicted to increase by 700% from 2014 to 2019 (Choma, 2015). These high levels of mobile phone use for texting make it important to study and understand the physical risks, especially among young people with developing musculoskeletal structures (Gustafsson et al., 2011). Regular excessive texting, over long periods of time, raises a concern for the likelihood of repetitive strain injury (RSI) occurring in the thumb, hand, and wrist.

Repetitive strain injury is an umbrella term that encapsulates various occupational and activity-induced upper extremity disorders (Fast, 1995). Texting has previously been associated with several types of RSI, including carpal tunnel syndrome and de Quervain's tenosynovitis (Ali et al., 2014; Gold et al., 2012). These associations have been made using therapeutic evaluation, magnetic resonance imaging (MRI), surface electromyography (EMG), and motion analyses (Ashurst et al., 2010; Gold et al., 2014; Jonsson et al., 2011). While the dynamics and forces of texting have been examined separately, a comprehensive analysis of thumb kinematics and kinetics while texting does

not yet exist. Quantifying the internal kinetics of texting may allow ergonomic recommendations for the prevention of RSI to be made.

Existing texting studies have measured EMG, phone contact forces, and joint postures (Gustafsson, 2011; Hogg, 2010; Trudeau et al., 2012), but have generally done so separately, with a subjective observational approach, meaning evidence of the internal forces and torques on the thumb as it moves through its three-dimensional workspace is limited (Hogg, 2010). Combining and improving methods of obtaining these outcome measures would allow for a more complete analysis.

One-handed texting is believed to have a large effect on joint loading, as it involves higher thumb velocities and muscle activity with fewer pauses (Gustafsson, 2011). In one study involving 859 participants, 44.4% habitually texted one-handed (Gold, 2012). Whereas able-bodied persons may switch to two-handed texting at the onset of discomfort, people with an upper limb loss do not have this option. It has been reported that people with upper limb loss who considered themselves to be regularly or always texting had higher pain levels in their sound limb than those who were occasional or non-texters (Biden et al., 2013). Investigating the effects of one-handed texting on the internal joint loading may further highlight connections to RSI.

When assessing the connection between texting and RSI, it is important to consider external factors such as other frequent activities of daily living (ADLs) or the physical characteristics of the cell phone being used. Excessive cumulative loads on the hand and wrist in ADLs, commonly seen in factory workers or athletes, can lead to upper limb disorders (Fast, 1995). Musculoskeletal symptoms, including pain, have also been found to correspond to significantly higher muscle activity and thumb velocities with fewer

pauses during texting (Biden, 2013; Sharan & Ajeesh, 2012). Considering symptoms that may be caused by ADLs could improve the understanding of how texting may be related to RSI.

1.2 Objective

The primary objective of this research was to evaluate the kinematics and kinetics of texting while (a) comparing one- and two-handed texting, (b) comparing people with upper limb loss to normally-limbed individuals, (c) evaluating the effect of hand to phone size ratio, and (d) exploring muscle activity of the flexor pollicis longus (FPL) and abductor pollicis brevis (APB). Primary outcome measures included net joint forces and torques, joint angles, thumb velocity, muscle activation occurrence, and muscle activation duration.

It was hypothesized that one-handed texting would result in higher contact forces on the cell phone screen compared to two-handed texting, resulting in larger joint loads. It was also hypothesized that participants with limb loss would have no significant difference in texting forces compared to normally-limbed participants, but would show differences in EMG activity due to previously existing musculoskeletal symptoms. Finally, hand to phone size ratio was expected to influence outcome measures in all participants, with joint loads predicted to increase with hand to phone size ratio. These hypotheses were based on personal observations.

It was expected that complexity and subjectivity of possible confounding variables that may have an effect on primary outcomes would be difficult to control. To address this, said variables were explored using results from a series of hand assessment tests, as well as demographic and ADL questionnaires.

Literature Review

1.3 Functional Anatomy of Texting

To discuss the mechanical functions of texting, one must understand the anatomical terminology involved. The anatomical position, shown in Figure 1, is used as a reference for describing anatomical structures (Drake et al., 2014). Planar and directional terms labeled in Figure 1 are used to describe the location of structures with respect to the center of the body. However, when describing a limb, a local reference or plane must be used. As a result, inconsistencies exist with terminology, particularly with the hand, and are defined for use in this study (Hollinshead & Jenkins, 1981).

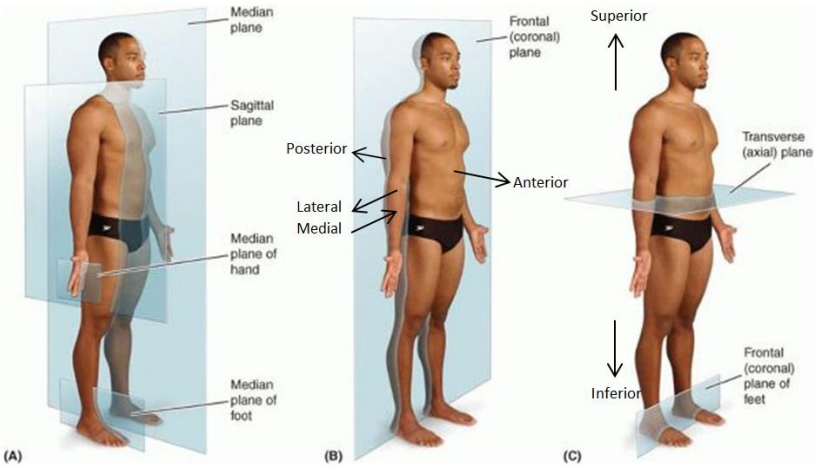

Figure 1. Anatomical planes. (A) The median plane, or midsagittal plane, bisects the body through the midline separating an equal right and left side; (B) The frontal plane separating the anterior and posterior surfaces of the body; (C) The transverse plane separating the superior and inferior sections of the body (Moore et al., 2014).

A unique set of anatomical terms exist for describing the hand. With respect to the median plane of the hand in the anatomical position, the thumb is located on the lateral or radial side, and the little finger is on the medial or ulnar side. Rather than having anterior and posterior surfaces, the hand has palmar and dorsal surfaces, respectively. The thumb is in the anatomical position when its palmar surface is approximately 90 degrees from the palm of the hand (Drake, 2014). This specific anatomical terminology is also used when describing the corresponding skeletal, muscular, and functional anatomy (Hollinshead, 1981).

1.3.1 Skeletal Anatomy

The thumb - the first digit of the hand - is the focus of this study. In contrast to the four fingers, the thumb only has a medial and distal phalanx. Movement of the thumb involves interaction of the phalanges, sesamoids, first metacarpal, and trapezium, shown in Figure 2. The interactions between the bones of the thumb provide many degrees of freedom (DOFs) and facilitate the prehensility of the hand (Kapandji, 1970).

Movement of the thumb is achieved by three synovial joints: interphalangeal (IP), metacarpophalangeal (MCP), and carpometacarpal (CMC). The degrees of freedom of the joints in the thumb allow a large range of motion and the ability to attain various postures (Drake, 2014).

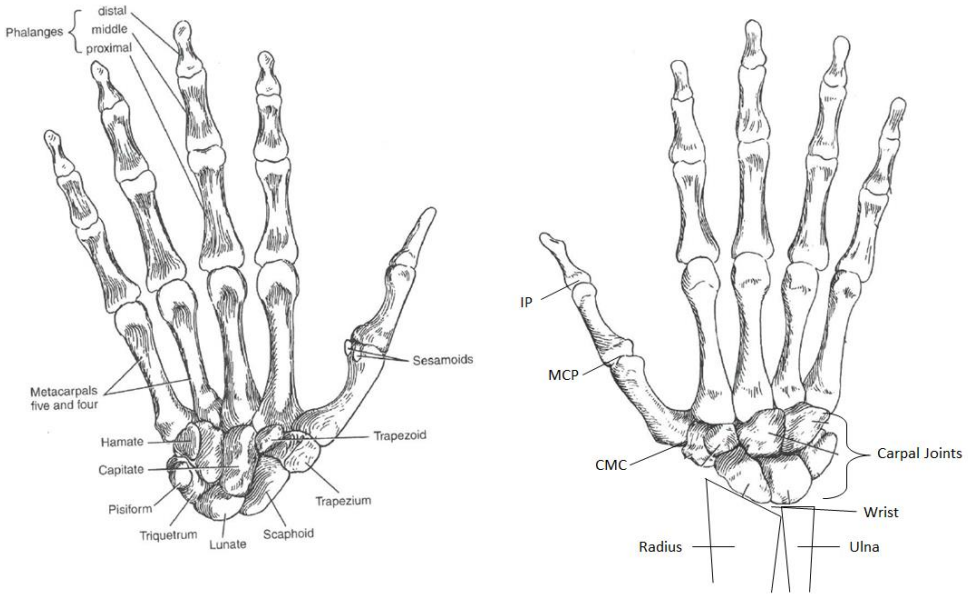

Figure 2. Bones and joints of the wrist and hand: palmar view (left) and dorsal view (right) (Hollinshead, 1981).

1.3.2 Thumb Postures

Movements defined with respect to the anatomical position occur within and around axes aligned with specific anatomical planes. Thumb movements are defined perpendicularly to the other digits: flexion and extension of the thumb occur in the frontal plane, while abduction and adduction occur in the sagittal plane (Figure 3). Thumb abduction and adduction are performed only by the MCP and CMC joints, whereas flexion and extension occur in all three joints. Opposition is the movement by which the distal end of the thumb meets the distal end of any other digit, and consists of both flexion and abduction of the thumb.

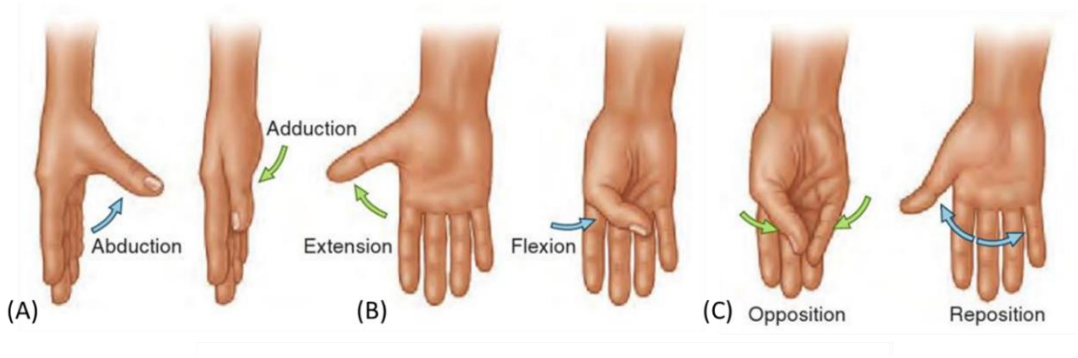

Figure 3. Movements of the thumb and wrist. (A) Abduction and adduction of the MCP joint in the sagittal plane; (B) Flexion and extension of the MCP and IP joints in the frontal plane; (C) Opposition and reposition of the CMC joint combined with flexion at the MCP joint (Moore, 2014).

1.3.3 Muscular Anatomy

Movements of the thumb are controlled by nine intrinsic and extrinsic muscles, located in the hand and forearm, respectively (Hamill & Knutzen, 2008; Kapandji, 1970). The extrinsic muscles that provide control of the thumb across the wrist include abductor pollicis longus (APL), extensor pollicis brevis (EPB), extensor pollicis longus (EPL), and flexor pollicis longus (FPL), and are illustrated in Figure 4. The intrinsic hand muscles that control the thumb (Figure 5) include flexor pollicis brevis (FPB), oppenens pollicis (OP), abductor pollicis brevis (APB), adductor pollicis (AP), and first dorsal interosseous (FDI). Note that OP, FPB, AD, and APB are the thenar muscles, which form the prominent swelling at the base of the thumb on the palmar surface called the thenar eminence (Drake, 2014). The muscles involved with particular thumb motions are summarized in (Kapandji, 1970).

Table 1. Muscle involvement in movements of the thumb (Kapandji, 1970).

Joint	Movement	Muscles
IP	Flexion	FPL
	Extension	EPL, FDI, APB
MCP	Flexion	APL, FPL, FDI, APB, FPB
	Extension	EPB, EPL
	Abduction	APB
	Adduction	AP
CMC	Reposition	EPL, AP, FDI
	Opposition	APL, FDI, APB, FPB, OP

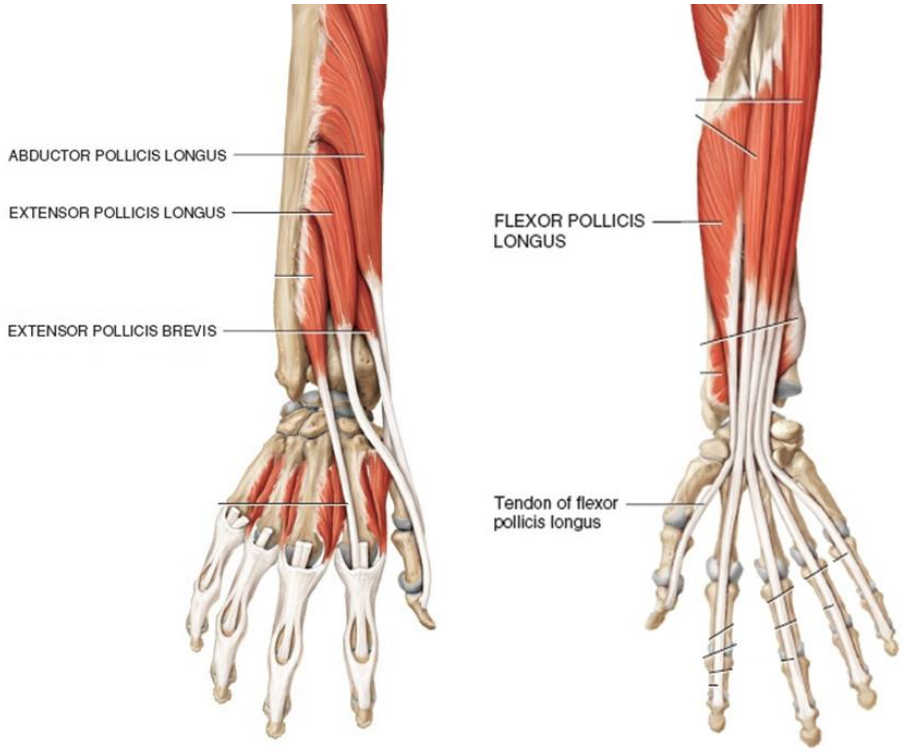

Figure 4. Extrinsic muscles of the thumb: posterior view (left) and anterior view (right) (Hollinshead, 1981).

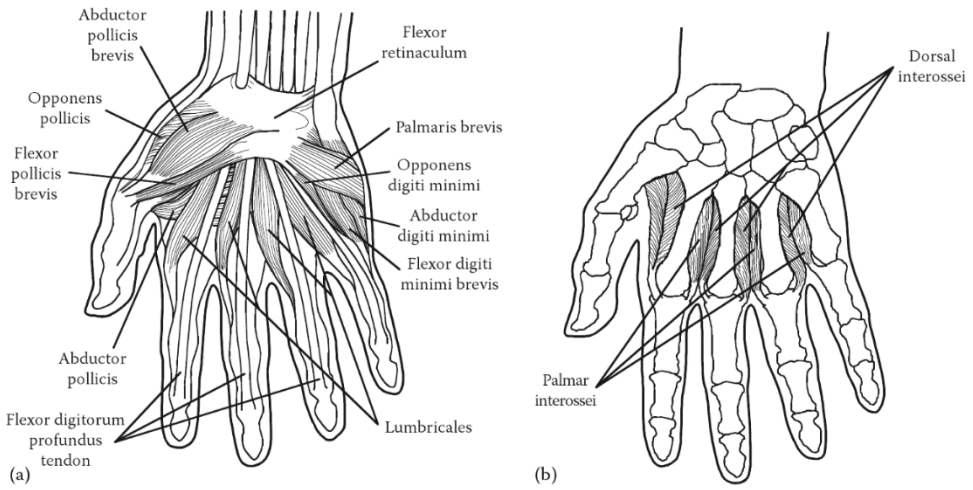

Figure 5. Intrinsic muscles of the hand: palmar view (left) and dorsal view (right) (Hollinshead, 1981).

1.4 Surface Electromyography and Texting

Existing texting studies have investigated myoelectric signals of all nine muscles of the thumb and reported extensive use during texting (Sharan, 2012). The primary muscles involved in texting have been identified as FPL, EPL, EPB, FDI, and APB (Brokenshire et al., 2009; Gustafsson et al., 2010). Muscle activity in the APB has been measured during texting using Myoscan Pro sensors and Triode electrodes, and was found to increase significantly during texting ((Lin & Peper, 2009)). Loads on active muscles during texting have been recorded as high as 18% of the corresponding maximum voluntary contraction (MVC) (Gustafsson, 2010). This level of activation exerted over long periods of time while completing fine motor tasks is known to cause symptoms of RSI (Oliver et al., 2007). This study investigates the total duration of muscle activation while texting to support these findings.

1.5 Texting Forces

Instrumentation for measuring texting forces is dependent on the type of cell phone being used. In 2012, the CWTA reported that 73% of Canadians use a smartphone, with an overall increase of 41% in smartphone use recorded yearly (Choma, 2015; Consulting Group, 2012). While many types of smartphone exist, 97% were predicted to be touchscreen by 2016 (ABI Research, 2011), therefore this study focused on instrumenting only touchscreen cell phones.

Cell phone touchscreens, with virtual QWERTY keypads, respond to surface capacitance rather than force. For this reason, existing research has neglected contact forces exerted by the thumb onto the screen. Despite force being unnecessary to activate the keys, notable forces are applied to touchscreens during texting (Hogg, 2010). A method for accurately measuring screen contact forces on touchscreen phones is required, and indeed crucial for carrying out an inverse dynamic analysis of texting.

1.5.1 Existing Instrumentation Methods

Many previous studies have instrumented the physical buttons on older cell phones, rather than touchscreens. One such study used a flat-ended Schaevitz linear variable differential transformer probe to measure axial load, i.e., the force perpendicular to the cell phone button (Hogg, 2010). The minimum force required to click the button was recorded and presumed to be the universal reaction force across all texting patterns. Average minimum texting forces for three different mobile devices were found to range from 1.62 N to 2.83 N, however these values were not applied to a kinetic model of the hand and wrist. Further investigation of the actual contact force of the thumb, as well as

the variation in contact forces for various texting patterns, remains necessary (Hogg, 2010).

A different keypad study measured contact forces on a Nokia phone with a three-by-four button numeric keypad. Forces were measured using a six-axis force/torque sensor mounted on the back side of the phone. The maximum contact forces did not exceed 6 N, while average forces for various texting tasks ranged from 1.0 N to 1.7 N. Measuring contact forces revealed that the thumb was, in fact, subjected to forces higher than the minimum force required for a keystroke. Unfortunately, the results may have been affected by the increased size of the device due to the sensor mount, which would necessarily interfere with the dynamics of texting (Redmond et al., 2010).

Touchscreen contact forces were measured using a force-sensing resistor during a study by Alavi and Biden (2015). A FlexiForce sensor, supplied by TekScan, was attached to the tip of the thumb using double-sided tape. Forces recorded during this experiment ranged from 0.14 N to 6.02 N, closely reflecting previous results, however the size of the sensor's surface area did not cover the entire thumb, which may have resulted in inaccurate or inconsistent force readings. Participants also reported texting with the sensor attached to the thumb to feel awkward and unnatural due to the physical interference by the sensor and associated hardware.

1.5.2 Instrumentation Selection Criteria

As the preceding two studies illustrate, accurately measuring touchscreen contact forces during texting requires appropriate instrumentation methods. The force sensor used for texting studies should be lightweight and small in size, to prevent any interference with the dynamics of texting, and highly resilient, to withstand repetitive loading over

long periods of time. Ideally, the sensor should also have a contact surface large enough to capture the entire thumb-to-screen contact area.

While these physical characteristics of force sensors are important, their functional characteristics – those that determine the accuracy and quality of the output signal - are equally critical, as they may limit the ability to measure texting forces accurately. Texting forces have been reported to range from 1 to 6 N (Redmond, 2010), meaning the ideal sensor should have a dynamic range that will allow all measurements to be recorded without reaching saturation. Smaller dynamic ranges lead to increased sensitivity and are therefore ideal for texting experiments (Fässler, 2010). Other functional characteristics such as hysteresis, repeatability, and linearity should be considered when selecting an appropriate force sensor.

1.6 Texting Parameters

1.6.1 Gender Differences

Existing studies that assess texting postures and muscular activity have used gender as a common point of comparison (Alavi, 2015; Gold, 2012; Sharan, 2012). Results have shown that women text in greater thumb abduction, with higher thumb velocities, and with fewer pauses compared to men. These results closely reflect those obtained for one-handed texters and those with musculoskeletal symptoms. Subsequently, women have also been reported to text with larger contact forces, likely due to increased muscle activity in ED and APL in women during texting (Alavi, 2015). As a possible result of these differences, the prevalence of de Quervain's tenosynovitis is higher in female texters (Ali,

2014). While comparing genders shows significant differences, investigating hand size may highlight more specific effects on various texting parameters.

1.6.2 Anthropometrics

Phone size has been suggested to affect significantly the thumb postures while texting (Gustafsson, 2010). Specifically, larger screen size has been reported to increase muscle activity as well as require larger range of motion for texting (Kietrys et al., 2015). While these results suggest that phone size is an important parameter to consider when analyzing texting, they have not lead to, for example, any suggestions for appropriate phone sizes for a given range of hand anthropometrics.

Hand anthropometrics such as those illustrated in Figure 6 have been investigated independent of phone size, with longer thumb length resulting in slower typing speed (Hogg, 2010). Another study evaluated hand size as the sum of circumference around knuckles, hand span, and hand length; using this hand measurement, it was found that those with larger hand sizes exerted smaller texting forces (Alavi, 2015). This was presumed to be due to the larger range of motion achieved across the iPhone 4 used in the experiment by those with larger hand sizes. Further investigation of hand to phone size ratio could increase the understanding of ergonomic cell phone use.

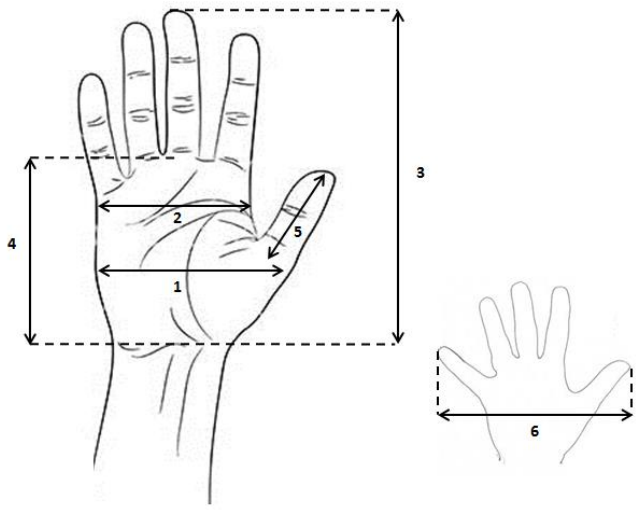

Figure 6. Anthropometric measurements of the hand. 1) Hand breadth (across thumb), 2) Hand breadth (metacarpal), 3) Hand length, 4) Palm length, 5) Thumb length, and 6) Maximum spread.

1.6.3 Key Location

The specific location, layout, and display parameters of virtual keypads on touchscreen phones may vary depending on the make and model of the phone, requiring the thumb to reach varying degrees of opposition while texting on virtual keypads (Gustafsson, 2010). Higher texting forces tend to be exerted on keys located closer to the CMC joint, i.e., those in the bottom right corner for a right-handed texter (Alavi, 2015). Forces exerted in this location have also been reported to require up to 56% more effort (Hogg, 2010). Thumb motor performance has also been reported to decrease in both the bottom-right and top-left corners of the keypad (Trudeau, 2012). In general, higher texting forces were recorded on the outer edge of the keypad compared to the center (Alavi, 2015). Therefore, an emphasis should be placed on the extreme locations of the keypad, where

contact forces have been reported to be higher, when investigating joint forces during texting.

1.7 Repetitive Strain Injury

Repetitive strain injury, also known as cumulative strain disorder or overuse syndrome, refers to a variety of pathologies of the upper limb. While the exact cause of RSI is unclear, it has been reported that cumulative microtrauma to soft tissues sustained through overuse and insufficient rest may contribute to the development of various conditions (Fast, 1995). Damage to biological tissues, such as inflammation, vascular and nerve compression, or fibrosis, may accumulate due to various ADLs.

Assessment of RSI is complex as it involves not only physical but also psychosocial evaluation, as it relies heavily on subjective reports of pain (Fast, 1995). A review of claims made to the workers' compensation board (WCB) of Manitoba in 1991 estimated that 9.3% of all upper limb claims were RSI; of these, tendonitis and carpal tunnel syndrome were the most common diagnoses at 27.5% and 19.3% of RSIs, respectively (Yassi et al., 1996). The frequency of RSI was heavily dependent on occupation: prior to the heavy usage of cell phones and computers, they were primarily found in manufacturing and meat processing. Moreover, claimants with RSI were less likely to return to work than those with non-RSI musculoskeletal injuries, therefore increasing the cost of RSI claims significantly. Further investigation of possible causes of RSI, particularly with the emergence of cell phones and computers as common work technologies, may ultimately lead to significant savings for WCBs worldwide.

Case studies completed in the last decade have diagnosed RSI specifically due to texting. One such case study positively linked de Quervain's tenosynovitis to excessive texting: physical evaluation using the Finkelstein test for de Quervain's tenosynovitis returned positive results, where Phalen and Tinel tests for carpal tunnel syndrome were both negative (Ashurst, 2010). Another study examined a patient with no previously existing musculoskeletal symptoms who was reported as an active texter for over three years (Ming et al., 2006). The patient was diagnosed with arthritis in the left and right CMC joint, and an X-ray showed partial dislocation of the left CMC joint. After successful arthroplasty and six months of avoiding excessive mobile phone use, the patient reported no pain in the left CMC joint, and the right was significantly improved (Ming, 2006).

Medical technology has been used to diagnose RSI and investigate the effects of texting. Bilateral ultrasound evaluations showed that excessive texters experienced FPL tendon thickening in the middle region of the thenar eminence (Akkaya et al., 2015). Tenosynovitis of the FPL tendon, as well as those of extensor carpi radialis brevis (ECRB) and extensor carpi radialis longus (ECRL), was also seen in high-volume texters using MRI (Gold, 2014). While these results suggest that ultrasonography, X-rays, and MRI may be indicated for more definitive diagnoses, studies with larger populations are required to validate these methods. Comprehensive modelling for quantifying the demands on soft tissue affected by texting may also be a basis for RSI prevention, though it has yet to be completed (Hogg, 2010).

1.8 Modelling the Thumb

Accurately modelling the thumb is important for providing a comprehensive biomechanics assessment during occupational tasks, including texting (Buczek et al.,

2011). In particular, realistic biomechanical models of the thumb are lacking due to the variability and uncertainty of musculoskeletal parameters (Valero-Cuevas et al., 2003). Understanding the kinematic behavior of the thumb by studying the individual joints is important for applying accurate models.

1.8.1 Kinematic Descriptions of Thumb Joints

The IP joint of the thumb is typically described as a hinge joint with one degree of freedom (Figure 7, top), allowing for flexion and extension of the distal phalanx of the thumb. Active extension at the IP joint is typically negligible, however larger ranges of passive extension can be achieved (Kapandji, 1970; Levangie & Norkin, 2011). While some models have included a second DOF representing any possible abduction and adduction (Endo, 2015), it is far more common to have only one DOF at the IP joint for simplicity's sake, as the complexities of the MCP and CMC joints already require more advanced models (Kapandji, 1970).

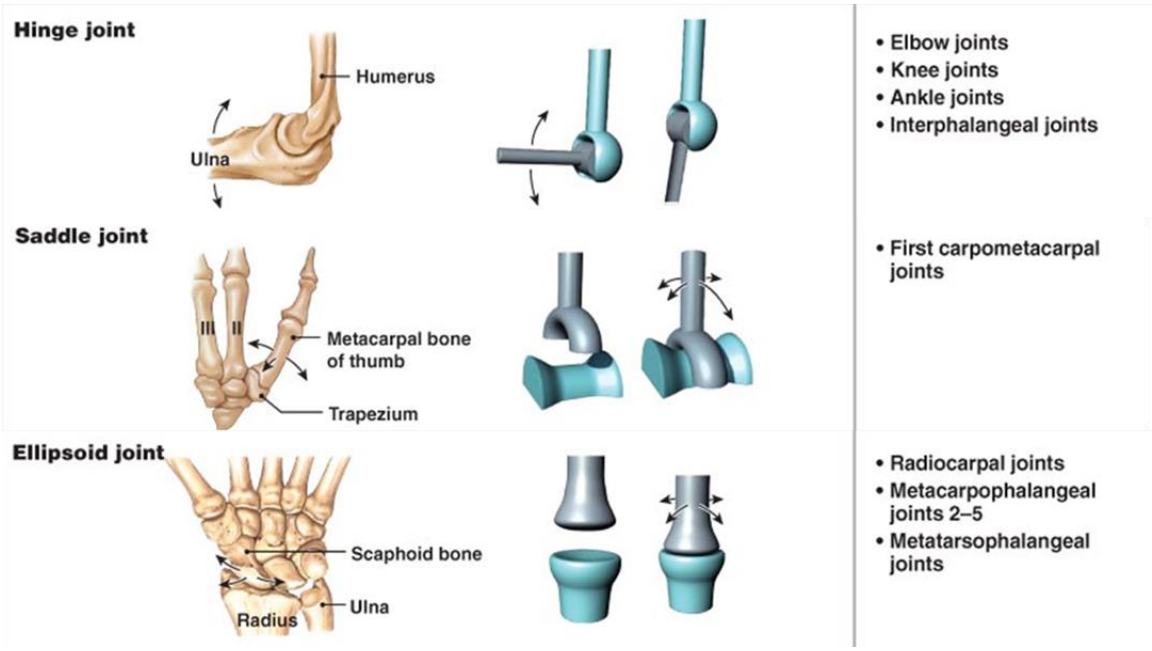

Figure 7. Examples and models of anatomical synovial joints (Martini et al., 2011).

The MCP joint is an ellipsoidal joint (Figure 7, bottom), and has been modeled in various ways. The MCP joint allows for flexion and extension along the frontal plane, as well as abduction and adduction along the sagittal plane (Kapandji, 1970). Typically, two DOF are used to model the MCP joint, however one and three DOF have been used as well (Endo, 2015; Valero-Cuevas, 2003). Using one DOF simplifies the allowable motion by neglecting abduction and adduction local to the MCP joint, however oversimplification has been reported to be an issue when using one or even two DOF to model the MCP joint (Hogg, 2010), and may lead to inaccurate transformation of thumb tip forces to joint forces and torques (Valero-Cuevas et al., 2003). Conversely, an additional DOF can be added to represent passive axial rotation due to the capsular laxity and incongruent articular surface (Levangie, 2011).

The CMC joint is a saddle joint (Figure 7, middle), and allows for the majority of thumb movements with respect to the hand (Kapandji, 1970). With the trapezium fixed, the first metacarpal can rotate about two axes along the frontal and sagittal planes, therefore providing two degrees of freedom. Muscles and ligaments surrounding the CMC joint maintain the joint in apposition, however the joint is relatively loose and some axial rotation occurs (Kapandji, 1970). Axial rotation at the CMC joint is referred to as rotation and circumduction, and can be modelled as a third DOF (Drake, 2014). These motions are crucial for achieving opposition of the thumb, and therefore should not be neglected.

The CMC joint experiences the most complex movements and should be modelled to account for all possible DOF. An advanced six-DOF model has previously been developed to account for all three DOF at the CMC joint (Buczek, 2011), however this model could be improved by also allowing for three DOF at the MCP joint as well. Exploring a model with seven DOF (one at the IP joint, and three at both the MCP and CMC) may address the concerns stated in existing models.

1.8.2 Motion Capture

When developing a marker set for capturing thumb motion, it is important to consider skin movement artifacts. Particularly in the area of the CMC joint, skin motion over the underlying bony segments affect the accuracy of motion capture (Kuo et al., 2002). Large skin movement artifacts of the thumb, when using full marker sets similar to that shown in Figure 8, have previously led to complete omission of thumb rotational and translational kinematic results (Buczek, 2011). Accuracy of marker placement on other anatomical landmarks must also be considered. A minimal marker set has been developed

to address both skin movement artifacts and marker placement error for thumb and finger movement and is also shown in Figure 8 (Nataraj & Li, 2013).

For this purpose of this study, a marker set was developed, using marker placement strategies similar to Buckzek's, however simplified to allow for 1 DOF at the IP joint, and 2 DOF at both the CMC and MCP joints.

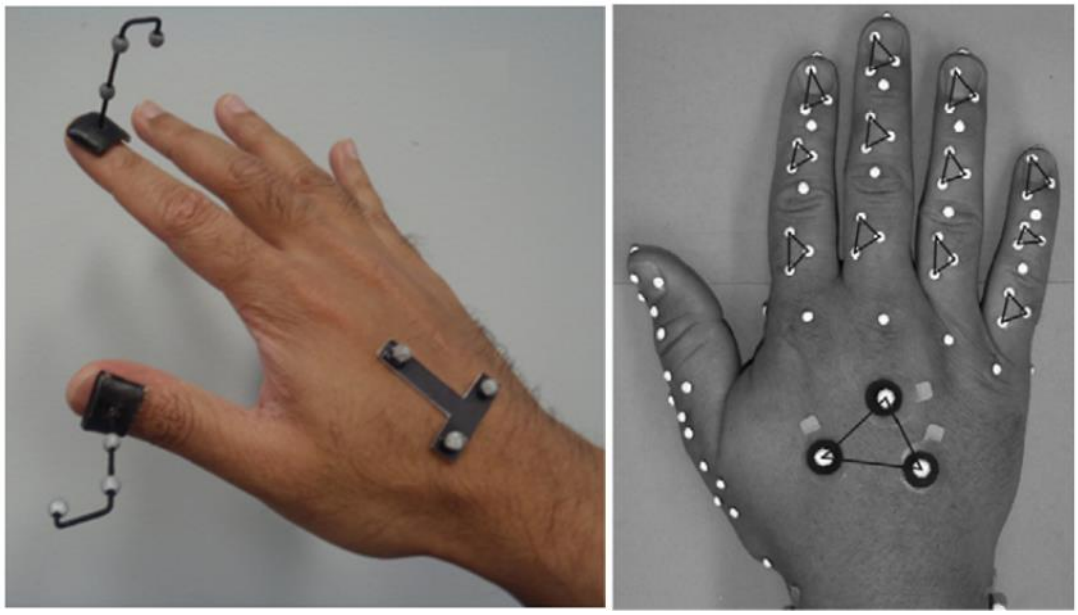

Figure 8. (Left) Minimal marker set (Nataraj, 2013) (Right) Full marker set with clusters on each segment (Buczek, 2011)

Methods

1.9 Subjects

For this study, participants were recruited to complete a variety of texting tasks. Data collection took place at the University of New Brunswick, Institute of Biomedical Engineering (IBME) motion lab. Participants were recruited by oral communication within the University of New Brunswick and local community, as well as by the Occupational Therapist at the Atlantic Clinic for Upper Limb Prosthetics. Participants in this study were between the ages of 17 and 53, where participants under the age of 19 were required to have signed consent from a legal guardian. People with a transradial or transhumeral, or congenital upper limb amputation were included in this study. Total participant numbers and demographics are outlined in Table 2.

Table 2. Participant Demographics

		Normally Limbed People	**People with Limb Loss**
Gender	Female	n = 8	n = 4
	Male	n = 8	n = 3
Age Range		18 – 53	17 - 41
Mean Age		24.9 ± 5.3	36.4 ± 11.3
Dominance or Side of Limb Loss	Right	14	2
	Left	2	5
Participants Involved in Texting Force + EMG		16	7
Participants Involved in Motion Capture		16	6

Research ethics approval was granted by the University of New Brunswick's Research Ethics Board, under file number 2016-058. Consent and full understanding of the procedures to which the participants were subjected to was collected using the consent form found in Appendix B: Informed Consent. All parties providing consent were fully informed that the participant would be exposed to less than minimal risk and that the participant's welfare will be protected throughout the duration of the experiment.

1.10 Musculoskeletal Assessments

Throughout the duration of the musculoskeletal assessments, data were recorded on Survey C, found in Appendix C: Participant Surveys. The same survey provided instruction and was used for measuring and recording the anatomical parameters of the participant's hand.

1.10.1 Phalen Test

The Phalen test checks for symptoms of carpal tunnel syndrome. Participants sat close to the edge of a table and rested their forearms on it while placing the dorsal side of their hands together and touching their fingertips to the center of their chest for two minutes (Figure 9). If the patient reported any pain through their wrist, or tingling and numbness in their fingers, then the test results were positive. Participants with limb loss completed this test by placing the dorsal side of their hand against a hard surface for the duration of the test.

Figure 9. Phalen test arm placement for normally limbed participants (Left) and for participants with limb loss (Right).

1.10.2 Finkelstein Test

The Finkelstein test checks for possible symptoms of de Quervain's tenosynovitis. Participants sat in a chair with no arm supports with their arm resting along their side, and elbow bent at approximately 90 degrees. They were then asked to fold their thumb into their palm and close their fingers to make a fist (Figure 10), and perform ulnar deviation of the wrist by bending it toward the floor. If the patient reported any pain between their thumb and forearm, the result was recorded as positive.

Figure 10. Finkelstein test arm position

1.10.3 Dynamometer Test

The participants' grip strength was recorded using a Jamar Plus hand dynamometer that measured up to 200 lbs. or 90 kg (Patterson Medical, Sammons Preston). While the participant sat comfortably in a chair with no arm rests, they were handed the dynamometer, which had been configured for their hand size, and asked to hold their arm along their side at an approximate 90-degree angle (Figure 11). Once the experimenter pressed the test button, the participant squeezed the dynamometer with their maximum effort. This result was recorded for analysis.

Figure 11. Dynamometer test arm position

1.11 Instrumentation and Software

1.11.1 Force Instrumentation

After testing various sensors eligible for force measurement, it was found that functional and physical properties of the SingleTact sensor were best suited for this study. These uniaxial sensors have a dynamic range of 10 N, a force resolution of 0.02 N, and a repeatability error of less than 1%. The SingleTact sensors came with a paired electronics board that was pre-calibrated by the manufacturer to have a linear output within the

desired range, with a linearity error of less than 2%. More sensor characteristics can be found in Appendix A: Force Sensors.

The force sensors' calibrations were independently measured before beginning this study to confirm the manufacturer's calibration specifications. This measurement was done using a Kistler Dual Mode Amplifier, a 50-pound (222.7 N) capacity piezoelectric load cell, and a Measurement Computing Data Acquisition (DAQ) System. The data collected from the force sensors and the load cell showed that the functional characteristics did indeed meet the manufacturer's specifications.

To measure texting forces, five SingleTact sensors were secured on the screen of the cell phone. One sensor was placed at each of the four outer corners of the virtual keypad to account for extreme forces and thumb postures (Alavi, 2015; Trudeau, 2012), while a fifth was positioned at the center of the virtual keypad as a reference (Figure 12). Sensor placement was repeatable throughout the entire experiment due to stickers that were previously placed in exact measured locations. For left handed participants, the sensor pattern was flipped around the longitudinal axis of the phone to allow for consistency, where sensors 1 and 3 are opposite the palm of the dominant hand.

Figure 12. Force sensor placement on a cell phone screen.

1.11.2 Motion Capture

A Vicon M-Cam motion system (Oxford Metrics, Oxford, England) at IBME was used for the motion capture of texting. Eight infrared cameras were arranged to create a small capture volume which was relatively symmetrical to account for both left- and right-handed participants (Vicon Motion Systems)(Figure 13). The cameras were calibrated before every capture, and set to a 60 Hz sampling rate. Care was taken to ensure cameras remained in the same location across all trials.

Participants were fitted with twelve 20 mm reflective markers on the body, and twelve 4 mm markers on the hand specifically. Although the focus of this study is the thumb, markers were also placed on the cell phone, wrist, arm, head, seventh cervical vertebra, anterior superior iliac spine (ASIS), and sacrum; a detailed description of this process is found in Appendix E. These additional markers were used for referencing the thumb and cellphone location in space, also for future observation of neck, trunk and

elbow postures. Only the dominant thumb, wrist, and arm, with which the participant completed the one-handed texting trials, were subsequently analyzed.

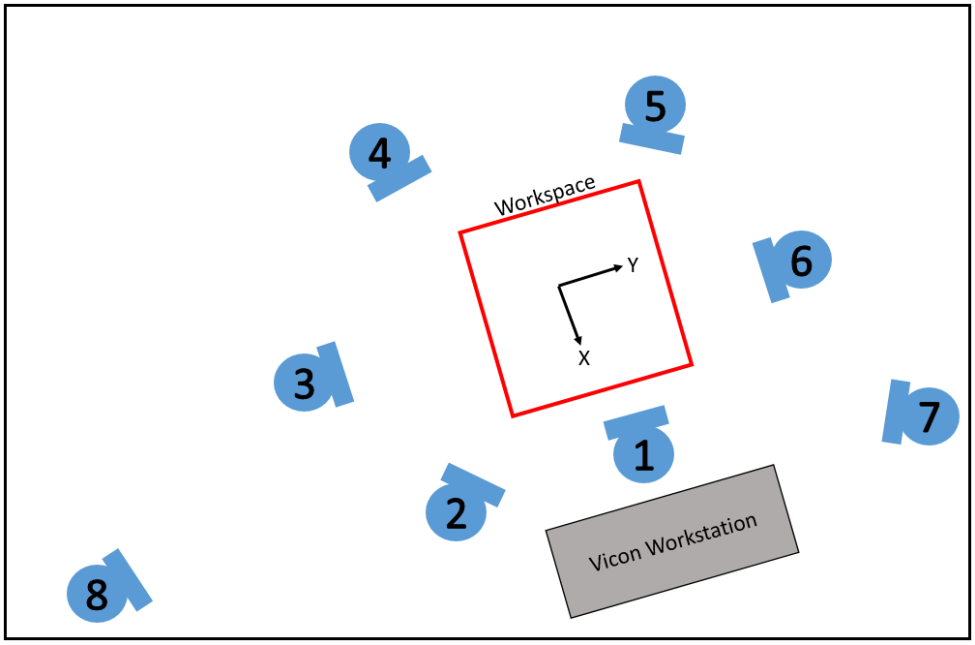

Figure 13. Camera layout, where cameras 1 through 6 were mounted on tripods at various heights, and cameras 7 and 8 were mounted on the wall.

A manual synchronization system was required to account for technical problems with the Vicon analogue input system. An infrared light in view of the cameras was triggered by the DAQ digital output channel and remained on for 60 frames, or one second, after which analog force and EMG data began recording.

Completed trials were processed using the Vicon software auto-labeling and gap filling features. Although these processes were automatic, every trial was inspected manually for the purposes of cropping for synchronization, as well as confirmation that the auto-labelling and gap filling features worked correctly.

1.11.3 Surface Electromyography

Myoelectric signals from FPL and APB were recorded to observe the overall duration of muscle activation during a texting trial. Maximum texting forces have been reported to occur at the bottom corner closest to the MCP joint (Alavi, 2015) where maximum range of motion in the IP and MCP joint occur (Hogg, 2010). The FPL and APB muscles were specifically chosen because they control flexion of the IP joint, and flexion and abduction of the MCP joint, respectively, and therefore would experience high activity when reaching to extreme locations on the cell phone screen. The duration of muscle activation, rather than the magnitude of the muscle potential, was examined, as duration has been reported to be directly related to RSI (Gustafsson, 2012).

Two different electrodes were used for collecting myoelectric data (Figure 16). A flexible concentric ring electrode, manufactured by Bioelletronica, was used to collect data from APB, because the flexibility and flat surface on the skin prevent any interference with the cell phone during texting. A fixed-distance two-site electrode, manufactured by Myotronics and referred to as a duotrode, was used for FPL because its physical characteristics were appropriate for the location of the FPL innervation zone. Both innervation site locations for the APB and FPL were selected based on the Atlas of Muscle Innervation Zones (Barbero et al., 2012).

Myoelectric data were collected using the same DAQ as the force sensors at 1000 Hz, and was therefore automatically synchronized with the force data. A custom 2 channel instrumentation amp-based EMG amplifier was used with a fix gain of 500 V/V. This instrumentation also included a 2^{nd} order high pass filter with a 16 Hz cut off frequency, as well as a 5^{th} order low pass filter with a 350 Hz cutoff frequency.

1.11.4 Graphical User Interface

A graphical user interface (GUI) was created to enable a comprehensive data collection (Figure 14). The GUI allowed the experimenter to enter unique file names, automatically sort and store data, delete and re-record trials, or resume a session partway through if an error occurred. When the Start button was clicked, analog data from the keypad sensors, and the two EMG channels were displayed live on the GUI screen. When the Stop button was selected, the analog data was automatically saved and the session incremented to the next trial number for storage. The complete data collection procedure is summarized in Figure 15.

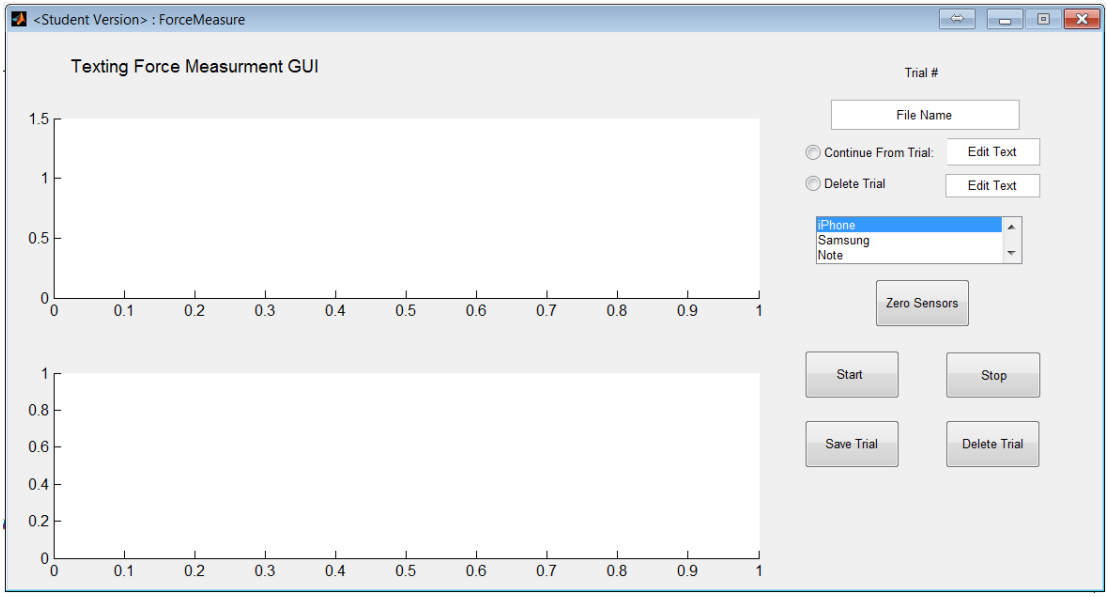

Figure 14. GUI designed and used for data collection. Texting force and EMG data for all channels were displayed as a live feed on the top and bottom axes, respectively.

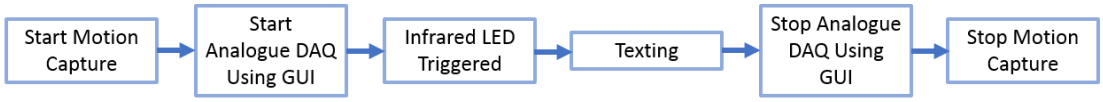

Figure 15. Overview of the procedure for an experimental trial.

1.12 Experimental Procedure

The experiment began with participants arriving at the IBME motion lab, then reviewing and signing the consent form. The experimenter performed the functional and anthropometric evaluation described in Appendix D and recorded the outcomes in Survey C (Appendix C: Participant Surveys). Next, participants with and without an amputation completed either Survey A or B, respectively, (Appendix C: Participant Surveys), providing their demographic information, details of their texting habits, and descriptions of other frequently performed ADLs.

Next, the participant was prepared for the main data collection by following a standard routine for applying EMG surface electrodes and reflective markers. Rubbing alcohol wipes were used to clean the skin surface in the area where the electrodes were placed. Using electrode site locating procedures suggested by the Atlas of Muscle Innervation Zones, the duotrode and concentric electrode were placed over the FPL and APB, respectively (Figure 16)(Barbero, 2012). These procedures included having participants pinch their pointer finger and thumb together, while the experimenter palpated the location of the respective muscles. A Red Dot electrode was placed on the medial epicondyle of the elbow to serve as ground. Electrodes were placed only on the dominant hand and arm. Care was taken to ensure adequate adhesion to the skin throughout the experiment. Reflective markers were then attached to the participant as outlined in

Appendix E: Complete Marker Set. The head and hip markers were secured with an elastic band, while the remaining markers were secured with double-sided tape. After the markers were attached, the participant was asked to enter the capture area.

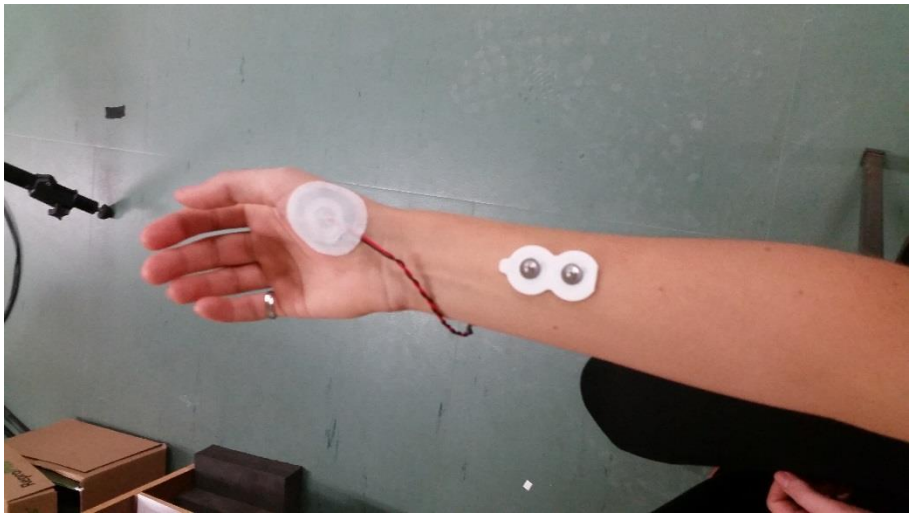

Figure 16. Concentric electrode (left) and duotrode (right) placed on APB and FPL, respectively.

During data collection, the participant sat on a chair with no arm supports (Figure 17), and did not rest their arms on their legs or any other possible support during data collection. Although the seated posture of the participant was not strictly controlled, participants were asked to avoid blocking the hip markers with their arms. Two texting patterns were followed throughout the experiment; the short pattern – typing 1 through 5 twice, and the long pattern – typing 1 through 5, 4 times (Figure 12). After a practice and familiarization period, the participant completed the short texting pattern 14 times, followed by another 14 trials using the long texting pattern. These 28 trials were completed for the three different sized phones resulting in a total of 84 trials.

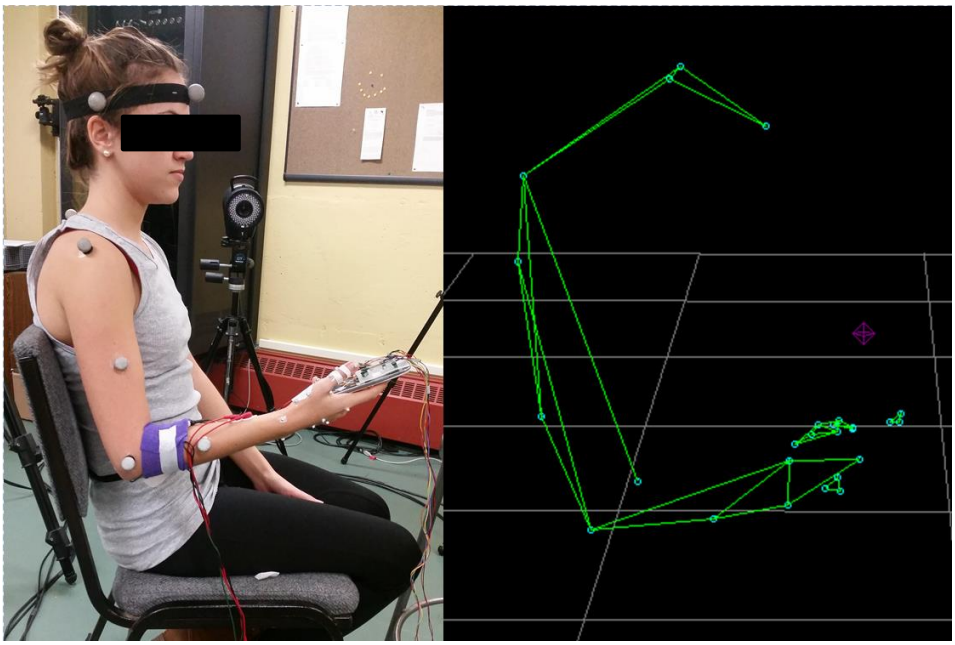

Figure 17. (Left**)** Participant in seated position completing a texting pattern. (Right) Corresponding capture in the Vicon software.

The three phones used in this experiment were the iPhone 4, Samsung Galaxy 3, and Samsung Note. Since there were only 5 force sensors available for this experiment, it was required to move the sensors when switching to a new phone. Small stickers indicating the specific sensor locations were on the phones at all times throughout the entirety of this experiment, which allowed for sensor placement repeatability. Physical properties of the phones are described in Appendix F: Phone Specifications.

While using the various phones, normally-limbed subjects alternated between one- and two-handed texting after each block of trials, while participants with limb loss only completed one-handed trials. Once all trials were recorded, the adhesive material attached to the participant was carefully removed and discarded. All data were saved to a database for future processing.

1.13 Analysis

Throughout the study, data collected during the experiment was manipulated and sorted into the structure outlined in Figure 18 using Matlab (verison R2015a, The MathWorks, Natick, MA, USA). Statistical analyses were completed using Minitab (version 17, Minitab Inc. State College, PS, USA).

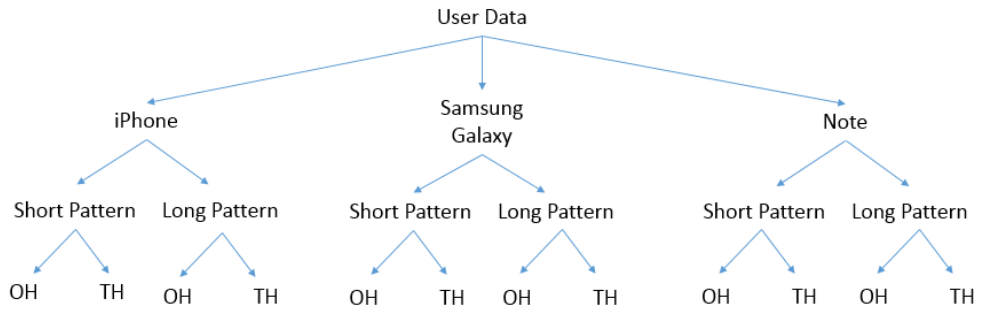

Figure 18. User data storage structure organized into phone type, pattern type and one-handed (OH) and two-handed (TH) texting.

1.13.1 Texting Force Analysis

Texting force data from the five capacitive sensors was filtered by a zero-lag 4th-order low-pass Butterworth filter with a cutoff frequency of 5 Hz, as well as a zero-lag 4th-order band-stop filter 57.5 Hz and 62.5 Hz to remove 60 Hz line noise. The filtered data, in volts, was converted to Newtons using the calibration equation provided by the sensor manufacturer. The local maxima of the force data were calculated, with the top two (short pattern) or four (long pattern) maxima highlighted as the key presses of interest. Mean force values for each sensor were found for every trial and normalized by the mean force at the center sensor.

The duration of a keystroke was defined as the time between the points at which the force on the sensor crossed a threshold value defined as

$$T = \mu + 2\sigma \quad (1)$$

where μ is the mean value of all force data less than 0.2 N and σ is the respective standard deviation. The impulse I of each keystroke was then approximated as:

$$I = F * D \quad (2)$$

where F is the force magnitude and D is the keystroke duration (Figure 19). The mean impulse for each sensor for every trial was calculated and saved into the data structure.

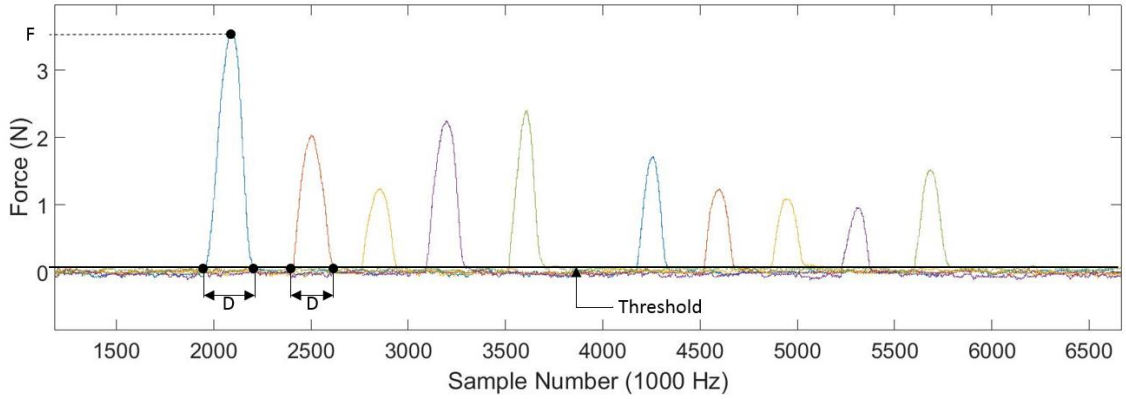

Figure 19. Example of forces plotted for a short pattern trial. *D* is the duration of the applied force and *F* is the magnitude.

1.13.2 EMG Analysis

The myoelectric data were also filtered by the same bandstop filter as described above to remove 60 Hz line noise, as well as a zero-lag 4th-order band-pass Butterworth filter at cutoff frequencies of 20 and 300 Hz. The data were filtered again using a moving average over a window of 100 samples. To recognize when a muscle was activated, a threshold was defined as

$$T = \mu + 3\sigma \tag{3}$$

where μ is the mean of the first 200 samples of resting data during a texting trial and σ is the respective standard deviation. The mean value of the noise during resting, plus three standard deviations, was chosen as an activation threshold to permit low-level contractions with very low probability (<1%) of activation due to the noise itself. The percent duration of muscle activation was then calculated as the total number of indices above the threshold divided by the total number of samples in the trial.

1.13.3 Motion Analysis

To simplify the analysis of the motion data, all marker trajectories were transformed so that the plane of the cell phone was coplanar with the global XY plane. To achieve this, the left cell phone marker was translated to the global origin (4) and all other markers were translated accordingly (5).

$$T_{origin} = \begin{bmatrix} 1 & 0 & 0 & -LCP_x \\ 0 & 1 & 0 & -LCP_y \\ 0 & 0 & 1 & -LCP_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$Markers' = T_{origin} * Markers \tag{5}$$

A local coordinate system (LCS) was defined on the cell phone by first defining the normalized vector along the *x*-axis of the LCS (6) and a temporary vector (7), where the vectors $\overrightarrow{RCP}$, $\overrightarrow{LCP}$, and $\overrightarrow{CCP}$ are illustrated in Figure 20.

$$\vec{V}_{phonex} = \frac{\overrightarrow{RCP} - \overrightarrow{LCP}}{\left|\overrightarrow{RCP} - \overrightarrow{LCP}\right|} \tag{6}$$

$$\vec{V}_{temp} = \frac{\overrightarrow{CCP} - \overrightarrow{LCP}}{\left|\overrightarrow{CCP} - \overrightarrow{LCP}\right|} \tag{7}$$

The orthogonal vector in the *z* direction was found by computing the cross product of the temporary vector with the *x* vector (8), which was then normalized (9).

$$\vec{V}_z = \vec{V}_{temp} \times \vec{V}_{phonex} \tag{8}$$

$$\vec{V}_{phonez} = \frac{\vec{V}_z}{\left|\vec{V}_z\right|} \tag{9}$$

Finally, the orthogonal vector along the *y*-axis of the cell phone LCS was found by computing the cross product of the *z* vector and the *x* vector (10) and then normalizing (11).

$$\vec{V}_y = \vec{V}_{phonez} \times \vec{V}_{phonex} \tag{10}$$

$$\vec{V}_{phoney} = \frac{\vec{V}_y}{\left|\vec{V}_y\right|} \tag{11}$$

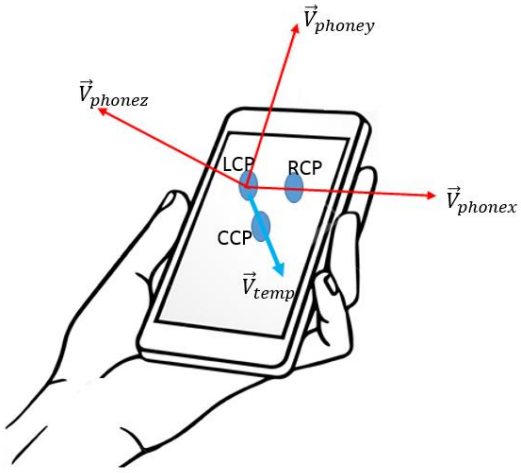

Figure 20. Cell phone LCS, where the blue dots represent the left (LCP), right (RCP) and center (CCP) cell phone markers, respectively. (Kluva, 2017)

The three normalized vectors along the cell phone LCS were used to define a rotation matrix (12) to align all marker data so the cell phone was parallel to the global XY plane (13), illustrated in Figure 21. These transformations were validated by checking that distances between markers did not change after rotation.

$$R_{phone} = \begin{bmatrix} \vec{V}_{phonex} & 0 \\ \vec{V}_{phoney} & 0 \\ \vec{V}_{phonez} & 0 \\ 0\ 0\ 0 & 1 \end{bmatrix} \tag{12}$$

$$Markers'' = R_{phone} * Markers' \tag{13}$$

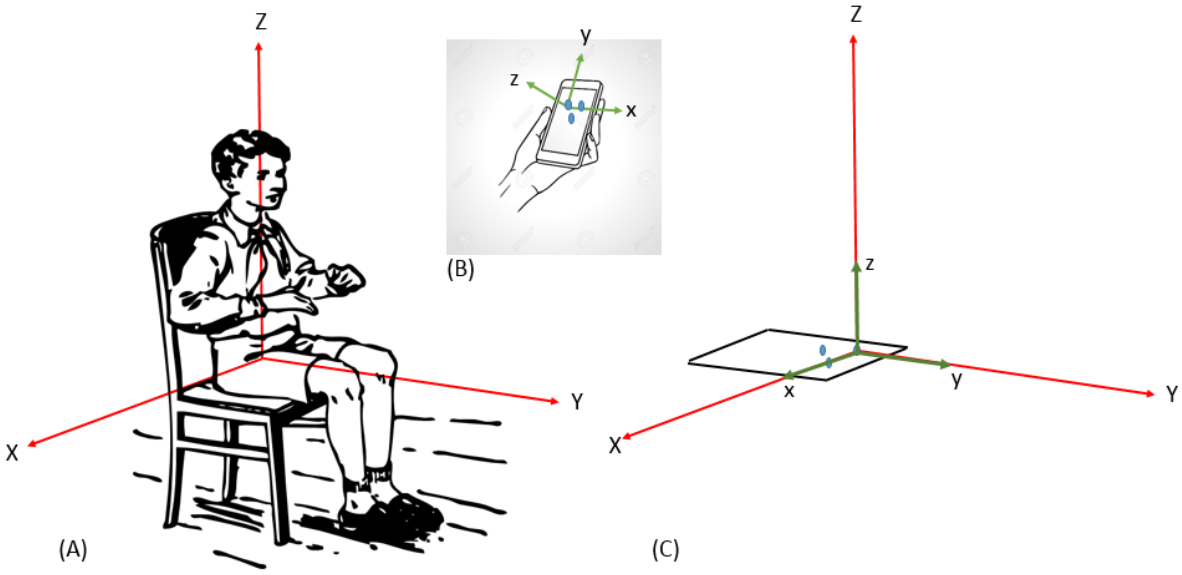

Figure 21 (A) Position of a participant in the capture area with global axes, (B) LCS of cell phone with origin at the left cell phone marker, (C) alignment of the cell phone LCS with the global coordinate system (GCS). (Kluva, 2017; "pixaboy," 2017)

Before calculating joint angles and torques, all motion data were up-sampled to 1000 Hz by linear interpolation to allow synchronization with the analogue data. Every trial was cropped to the sample at which the light disappeared; trials in which the Vicon cameras did not record the infrared light for the full 60 frames were synchronized by matching the indices of the first keystroke in the force and motion data. For every trial, synchronization was visually confirmed by plotting the force data against the height of the thumb in the z-axis, shown in Figure 22, and correcting any error manually.

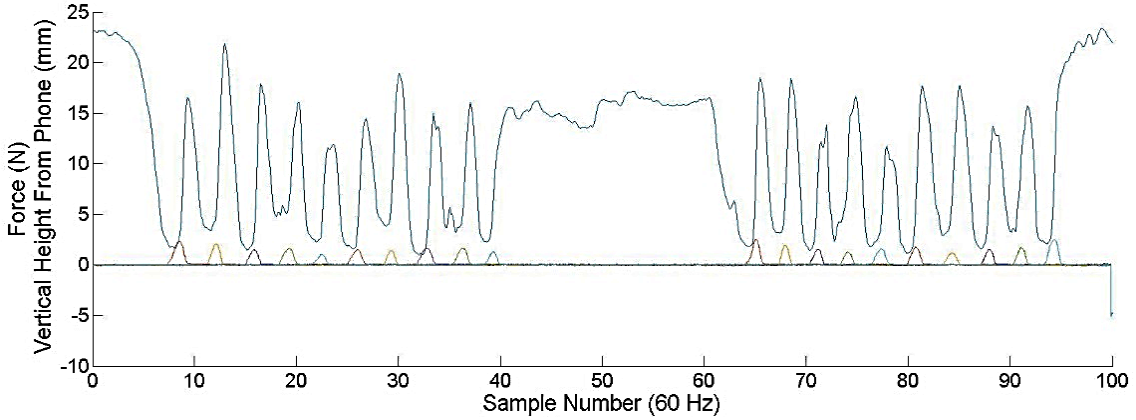

Figure 22. Sample of texting trial data including thumb height (upper data line) and keystrokes (lower data lines). The thumb height local minima were matched with the keystroke local maxima for confirmation of synchronization.

Joint centers were then defined as the midpoints between the medial and lateral IP (14) and MCP (15) joints, respectively, and used for future calculations as virtual markers (Figure 23). Net joint torque at each joint was calculated by computing the magnitude of the cross product of the force vector and the distal phalanx segment (16, 17). These vectors used to find the net joint torques are illustrated in Figure 24.

$$\overrightarrow{IP}_{mid} = \frac{\overrightarrow{IPM} + \overrightarrow{IPL}}{2} \tag{14}$$

$$\overrightarrow{MCP}_{mid} = \frac{\overrightarrow{MCPM} + \overrightarrow{MCPL}}{2} \tag{15}$$

$$T_{IP} = \left|\overrightarrow{DP_y} \times \vec{F}\right| \tag{16}$$

$$T_{MCP} = \left|\overrightarrow{PP_y} \times \vec{F}\right| \tag{17}$$

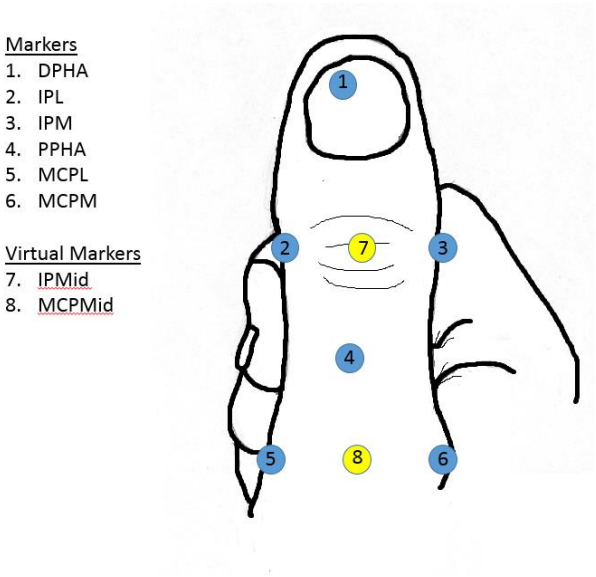

Figure 23. Thumb marker set layout. Markers were placed on thumb landmarks including: 1) distal phalanx (DPHA), 2) lateral IP joint (IPL), 3) medial IP joint (IPM), 4) proximal phalanx (PPHA), 5) lateral MCP joint (MCPL), 6) medial MCP joint (MCPM), and virtual markers at the midpoint of the 7) IP joint and the 8) MCP joint.

Next, the joint angles of the IP and MCP joints were calculated. This required defining the segments of the distal (18) and proximal (19) phalanges, as well as the first metacarpal (20).

$$\overrightarrow{DP} = \overrightarrow{DPHA} - \overrightarrow{IP}_{mid} \quad (18)$$

$$\overrightarrow{PP} = \overrightarrow{IP}_{mid} - \overrightarrow{MCP}_{mid} \quad (19)$$

$$\overrightarrow{MET1} = \overrightarrow{CMC} - \overrightarrow{MCP}_{mid} \quad (20)$$

The angle of the IP joint has one degree of freedom, and was calculated as the dot product between the distal and proximal phalanx segments (21).

$$\theta_{IP} = \arccos\left(\frac{\overrightarrow{DP_y} \bullet \overrightarrow{PP}}{\left\|\overrightarrow{DP_y}\right\|\left\|\overrightarrow{PP}\right\|}\right) \quad (21)$$

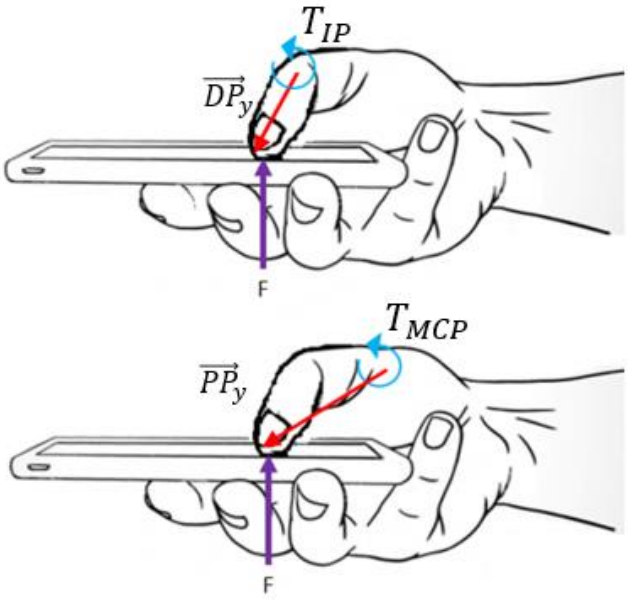

Figure 24. Force vector in purple was crossed with segment vectors in red to find net torque values in blue at the IP joint (top), and the MCP joint (bottom). (Sigova, 2017)

The MCP joint, however, has two degrees of freedom. To distinguish between the two angles, a LCS on the first metacarpal was defined using a similar procedure as before, with the origin located at the CMC marker (22 – 27). The second MCP joint marker was used to define the first metacarpal LCS so that the XY plane intersected the CMC, MCP_{mid}, and MET2 markers (Figure 28). A rotation matrix was then used to transform the proximal phalanx segment into the first metacarpal frame of reference (28). This first metacarpal LCS is illustrated in Figure 25.

$$\vec{V}_{metx} = \frac{\overrightarrow{MCP}_{mid} - \overrightarrow{CMC}}{\left|\overrightarrow{MCP}_{mid} - \overrightarrow{CMC}\right|} \quad (22)$$

$$\vec{V}_{temp} = \frac{\overrightarrow{MET2} - CMC}{\left|\overrightarrow{MET2} - CMC\right|} \tag{23}$$

$$\vec{V}_{metz} = \vec{V}_{temp} \times \vec{V}_{metx} \tag{24}$$

$$\vec{V}_{metz} = \frac{\vec{V}_{metz}}{\left|\vec{V}_{metz}\right|} \tag{25}$$

$$\vec{V}_{mety} = \vec{V}_{metz} \times \vec{V}_{metx} \tag{26}$$

$$\vec{V}_{mety} = \frac{\vec{V}_{mety}}{\left|\vec{V}_{mety}\right|} \tag{27}$$

$$R_{phone} = \begin{bmatrix} \vec{V}_{metx} & \mathrm{CMC_x} \\ \vec{V}_{mety} & CMC_y \\ \vec{V}_{metz} & \mathrm{CMC_z} \\ 0\ 0\ 0 & 1 \end{bmatrix} \tag{28}$$

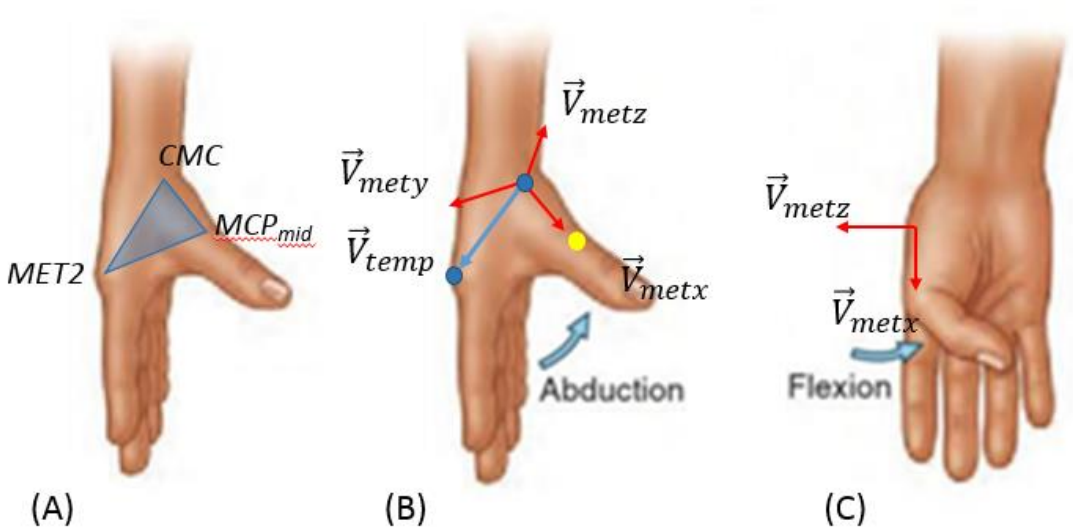

Figure 25. LCS of the first metacarpal with the origin at the CMC joint. (A) The XY plane is coplanar with the three markers: CMC, MCP_{mid} and MET2. (B) The LCS that was defined using the temporary

vector to allow for the abduction-adduction angle of the MCP joint to be the projected angle onto the XY plane. (C) The flexion-extension angle of the MCP joint is the projected angle onto the XA plane of the first metacarpal LCS (Moore, 2014).

For the abduction-adduction angle of the MCP joint, the dot product of the proximal phalanx and first metacarpal segments was computed in the XY plane of the first metacarpal LCS (29). Similarly, the flexion-extension angle of the MCP joint was found using the dot product of the same segments, however in the XZ plane of the first metacarpal LCS (30).

$$\theta_{MCPAB} = \arccos\left(\frac{\overrightarrow{PP_{xy}} \bullet \overrightarrow{MET1_{xy}}}{\left\|\overrightarrow{PP_{xy}}\right\|\left\|\overrightarrow{MET1_{xy}}\right\|}\right) \tag{29}$$

$$\theta_{MCPEX} = \arccos\left(\frac{\overrightarrow{PP_{yz}} \bullet \overrightarrow{MET1_{yz}}}{\left\|\overrightarrow{PP_{yz}}\right\|\left\|\overrightarrow{MET1_{yz}}\right\|}\right) \tag{30}$$

Finally, the maximum thumb speed was calculated using the motion data at its original 60 Hz sampling rate using a differential approximation (31-33).

$$\vec{V}_x[N] = \frac{DPHA_x[N] - DPHA_x[N-1]}{\frac{1}{f_S}} \tag{31}$$

$$\vec{V}_y[N] = \frac{DPHA_y[N] - DPHA_y[N-1]}{\frac{1}{f_S}} \tag{32}$$

$$\vec{V}_z[N] = \frac{DPHA_z[N] - DPHA_z[N-1]}{\frac{1}{f_S}} \tag{33}$$

where all velocities were assigned the initial value $\vec{V}[0] = 0$.

The magnitude of the velocity trajectory was calculated for the trial and the maximum value was stored in the user data structure.

The final variable analyzed in this study was phone stability, defined as the variance in roll, pitch and yaw angles of the phone. Based on the local coordinate system of the cell phone (Figure 21B), variance in roll, pitch and yaw occurred about the x-axis, y-axis, and z-axis, respectively (Figure 26). These angles were calculated using the unit vectors of the cell phone local coordinate system (34 – 36).

$$roll = \tan^{-1}\left(\frac{V_{phoney_x}}{V_{phonex_x}}\right) \tag{34}$$

$$pitch = \tan^{-1}\left(\frac{V_{phonez_x}}{\sqrt{V_{phonez_y}^2 + V_{phonez_z}^2}}\right) \tag{35}$$

$$yaw = \tan^{-1}\left(\frac{V_{phoney_y}}{V_{phonex_z}}\right) \tag{36}$$

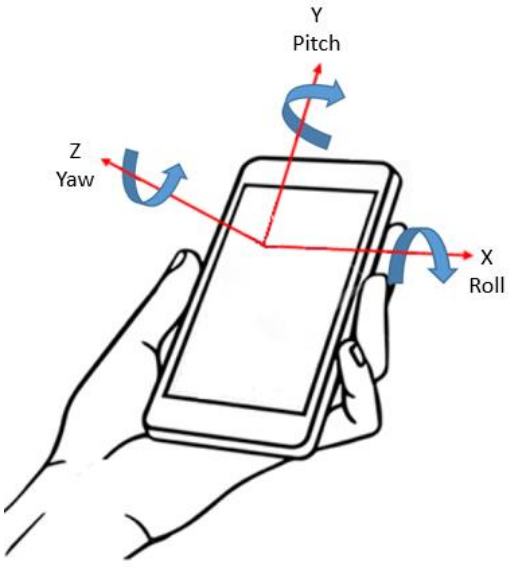

Figure 26. Roll, pitch and yaw about the cell phone LCS axes. (Kluva, 2017)

1.14 Statistical Analysis

This is an observational study where multiple variables were checked for correlation with a given response. Specifically, handedness (one- or two-handed texting), participant type (normally-limbed or person with an amputation), and hand to phone size ratio were all responses of interest. Binary logistic regression was used to form predictive models for categorical responses, handedness and participant type. Predictive variables (X_n) that had a significant effect on the response variable were assigned a coefficient and entered into the regression equation (34-35). Using the regression model for handedness, it was intended to determine if participants with limb loss could be identified as one-handed texting.

$$Response = \frac{e^{Y'}}{1 + e^{Y'}} \tag{34}$$

$$Y' = C + AX_1 + BX_2 + \cdots + DX_n \tag{35}$$

Stepwise linear regression was used to investigate hand to phone size ratio as it is a continuous response. The Bonferoni correction factor was used in both types of regression analyses to account for the increase in uncertainty due to the large number of predictive variables. Predictive variables that were significant in the models were checked individually for differences between response variable groups using *t*-tests.

Results

1.15 One-Handed vs. Two-Handed Texting

A binary logistic regression was conducted to evaluate which texting variables were necessary to predict one-handed or two-handed texting. This was completed using data from only the normally limbed participants. The Bonferroni correction factor determined a required significance of p = 0.003 for a predicitve variable to be entered into the model. The regression analysis resulted in an R^2 value of 0.85. Predictive variables that had significance in the model are listed in Table 3, and refer to notation in equations 34-35. Based on the results from the regression analysis, t-tests were conducted on individual variables to compare the differences between one and two-handed texting.

Table 3. Stepwise Multiple Regression for One-Handed vs. Two-Handed Texting

Predictor (X_n)	**Chi Squared**	**Coeffecient**
Texting Rate	163.14	A = -2.640
APB Activation Duration	72.49	D = 10.58
Thumb Velocity	66.63	B = 0.01065
IP Joint Torque	34.45	E = -0.0709
MCP Joint Torque	15.092	F = 0.02083
Regression Constant	C = 3.21	

Texting rate, in keystrokes per second, was the most significant predictive variable in the regression model based on the Chi Squared value. A two way t-test showed that texting rate is significantly higher during two-handed texting (p=0.000) (Figure 27). Thumb velocity, however, was significantly greater for one-handed texting (p=0.000)

(Figure 28). This means that during one-handed texting, although the number of completed keystrokes in a given time is less, thumb speed is faster.

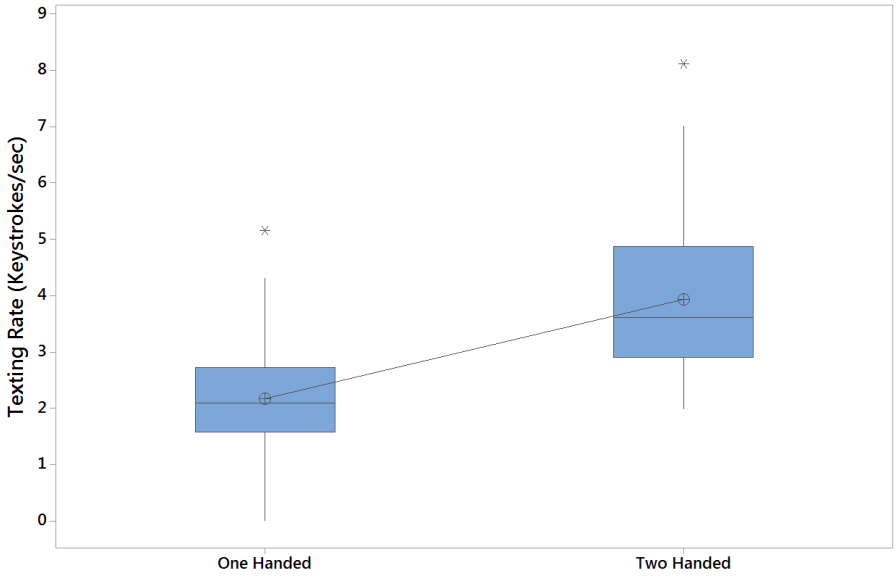

Figure 27. Comparison of texting rate between one-handed and two-handed texting.

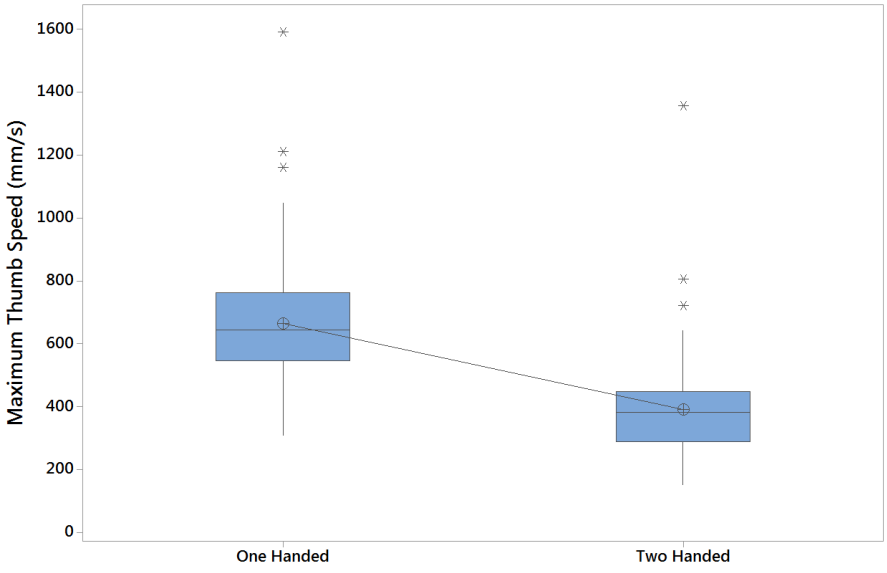

Figure 28. Comparison of maximum thumb speed between one-handed and two-handed texting.

Duration of the APB activation was also a significant predictive variable in the regression model. The difference in the duration of APB activation between one and two-handed texting was found to be significant when using a t-test (p=0.000). Significantly more APB activation occurred during one-handed texting (Figure 29).

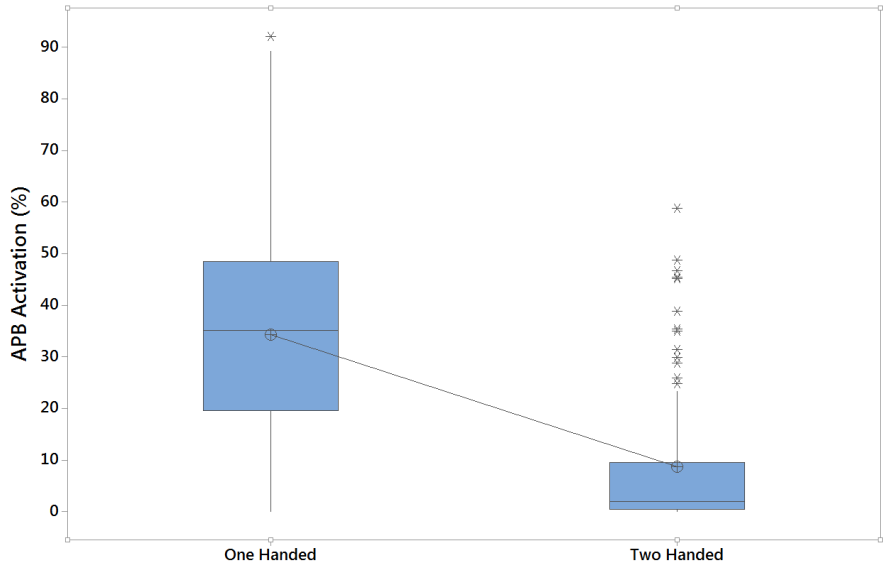

Figure 29. Boxplot illustrating the difference between APB activation as a fraction of the total trial time during one-handed and two-handed texting.

Texting force, although not a significant predictor variable in the regression model, was also investigated using a t-test. Overall, texting force showed a significant difference between one and two-handed texting (p=0.000). Only data from the second and fourth sensors were considered for the comparison of forces, because they were the only sensors used by the dominant hand during both one and two-handed texting. Sensors 2 and 4, in the force sensor layout (Figure 12), are located on the same side of the phone as the palm of the dominant hand. T-tests were individually completed to compare one and two-handed texting for sensors 2 and 4, both showing a significant difference with p-values of

0.002 and 0.044, respectively (Figure 30; Figure 31). In both cases, larger forces were exerted during two-handed texting.

The remaining predictive variables in the regression model were also checked using t-tests, and showed no significant difference between one and two-handed texting.

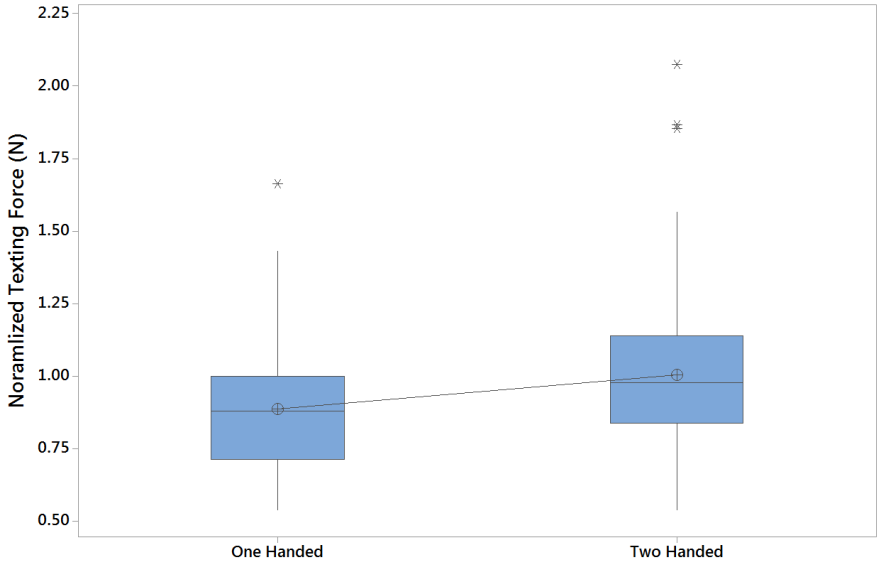

Figure 30. Comparison of normalized force on sensor two. Larger forces were exerted on the second sensor during two-handed texting, compared to one-handed texting.

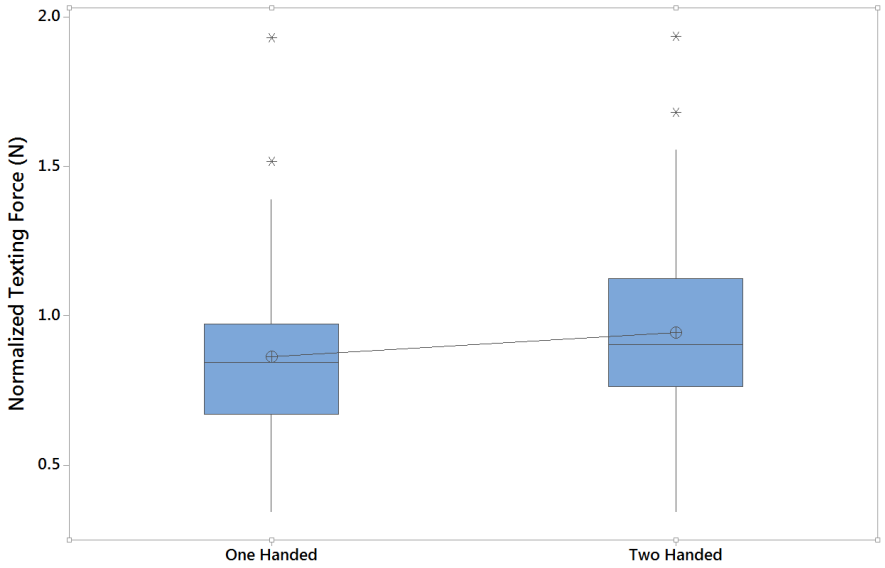

Figure 31. Comparison of normalized forces on sensor 4. Larger forces were exerted on the fourth sensor during two-handed texting, compared to one-handed texting.

1.16 Effects of Having Limb Loss

A binary logistic regression was also conducted to evaluate which texting variables were necessariy to predict if a participant did or did not have limb loss. Using the same procedure as the one and two-handed regression, a model with an R^2 value of 0.28 was found. Although the predictivess of this model was low, when entering data from the participants with limb loss into the handedness regression model discussed in section 4.1, all 210 data entries were classified correctly as texting one-handed. The variables used in the handedness regression model may highlight variables that may play a role for assessing risk for RSI. All responses were above 0.81, where the classification is one-handed as the response approaches 1, and two-handed as the response approaches 0.

Predictive variables that had significance in the participant type model, less than p = 0.007, are listed in

Table 4, and refer to notion used in equations 34-35. Again, t-tests were conducted to compare the differences between participants with and without limb loss.

Table 4. Stepwise Multiple Regression Predictors – People with Limb Loss vs. Normally Limbed

Predictor (X_n)	**Chi Squared**	**Coeffecient**
MCP Joint Abduction-Adduction Angle	45.64	A = -0.00824
Texting Rate	42.14	B = 0.0782
Finkelstein Test	34.13	D = 1.468
IP Joint Angle	21.60	E = -0.0732
Regression Constant	C = -0.061	

Significant differences between participants with and without limb loss were found in texting rates and IP joint angles. T-test results showed that people with limb loss experienced significantly slower texting rates than normally limbed (p=0.005)(Figure 32). Moreover, people with limb loss also texted with significantly smaller IP joint angles (p = 0.002) (Figure 33). All other variables in the regression model were investigated individually with t-tests, and no significant differences were found.

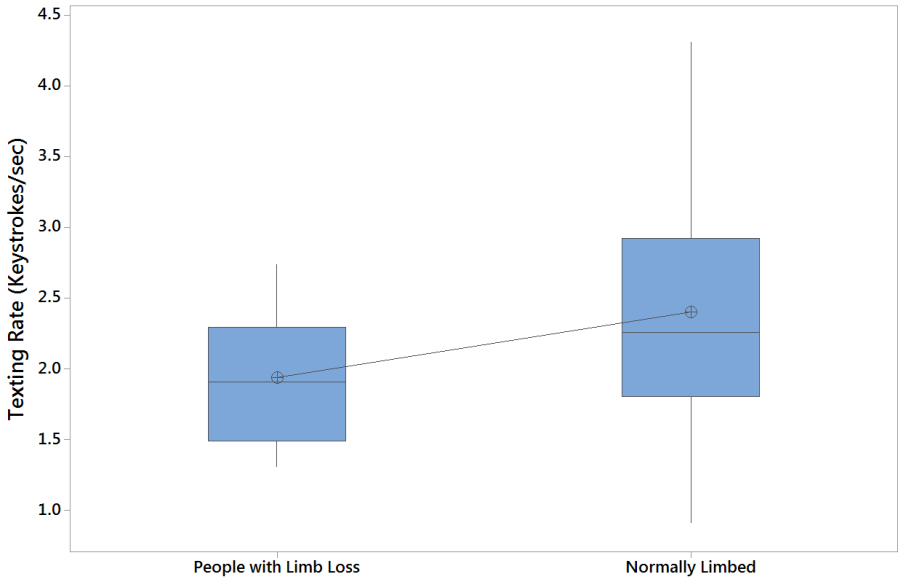

Figure 32. Comparison of texting rate between people with limb loss and normally limbed participants.

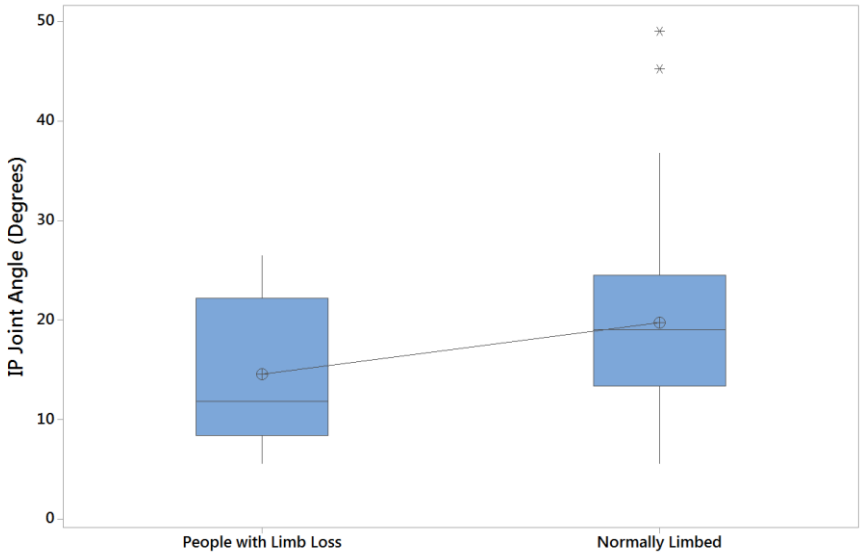

Figure 33. Comparison of IP joint angle between people with limb loss and normally limbed participants.

Phalen and Finkelstein test results were compared between people with and without limb loss. Overall, 6 out of the 7 participants with limb loss had positive results for both the Phalen and Finkelstein tests. However, only 7 out of the 16 normally limbed

participants had positive results for both tests. To support these findings, results from the pain scales in surveys A and B, found in Appendix C: Participant Surveys, were compared. Specifically, pain in the thumb, wrist and forearm during relaxation and texting were observed (Figure 35). In almost every scenario, people with limb loss reported higher pain levels than those without limb loss. More pain was experienced during texting for all participants, with the exception of wrist pain being higher during relaxation in people with limb loss. A summary of ADL's that could affect these results are summarized in Appendix G: Activities of Daily Living.

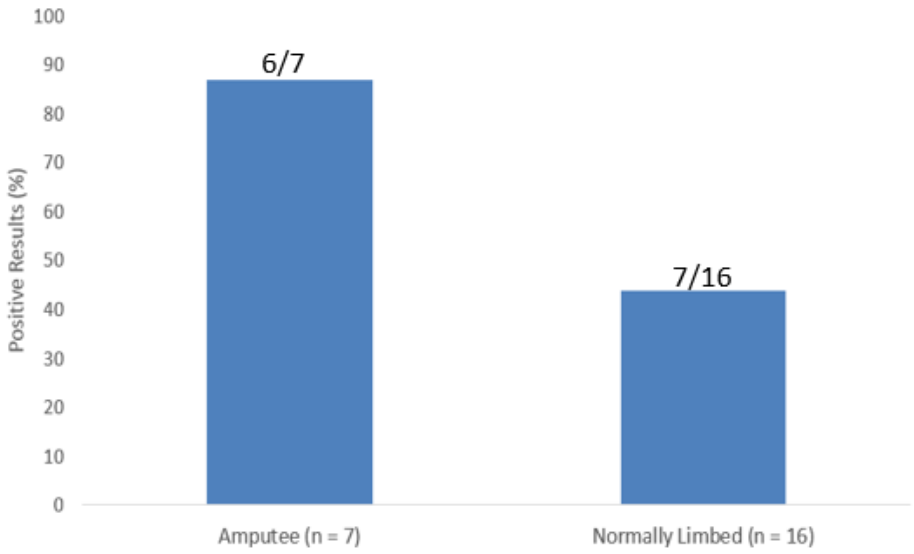

Figure 34. Histogram showing that people with an amputation have significantly higher positive results for the Finkelstein and Phalen tests.

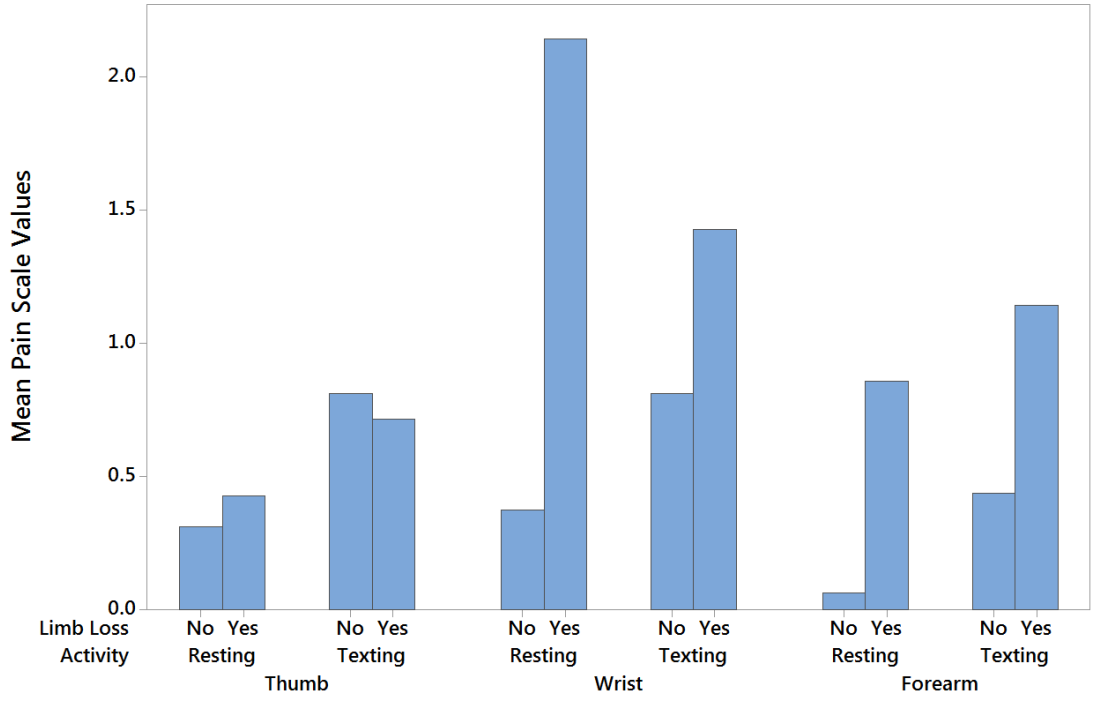

Figure 35. Comparison of mean pain scale values in the thumb wrist and forearm, between people with and without limb loss, during resting and texting. Pain scale values were measured out of a maximum 10 points, being the worst pain imaginable.

1.17 Gender Differences

Results reported in this study that are compared using gender, may in fact be due to hand size. Anthropometrics is an area of research that has been thoroughly investigated and show that males generally have larger hands than females (Pheasant, 1986). Results from this study support the fact that males have significantly larger hands than women, particularly the breadth across the base of the thumb (p=0.000) (Figure 36).

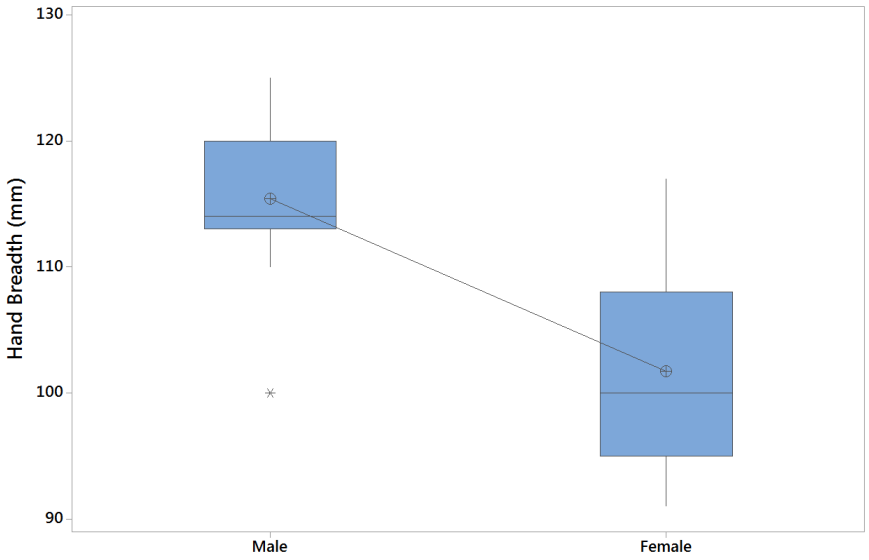

Figure 36. Comparison of hand breadth across the base of the thumb between genders. The male outlier in this figure was a participant who had a partial hand amputation, reducing the breadth.

Additional to hand size, strength and endurance also differ between genders, and may contribute to differences in texting outcomes (Nicolay & Walker, 2005). Although there was no significant difference found in dynamometer scores when comparing genders in this study, there was a significant difference between texting impulses. Females were found to text with significantly larger impulse than males ($p = 0.000$) (Figure 37). This may be due primarily to texting rates, as males texted significantly faster ($p = 0.000$), leading to a shorter keystroke duration. Texting rate is believed to be the primary cause of the difference in impulse because, although there is significance ($p = 0.049$), males texted with only slightly larger forces than females.

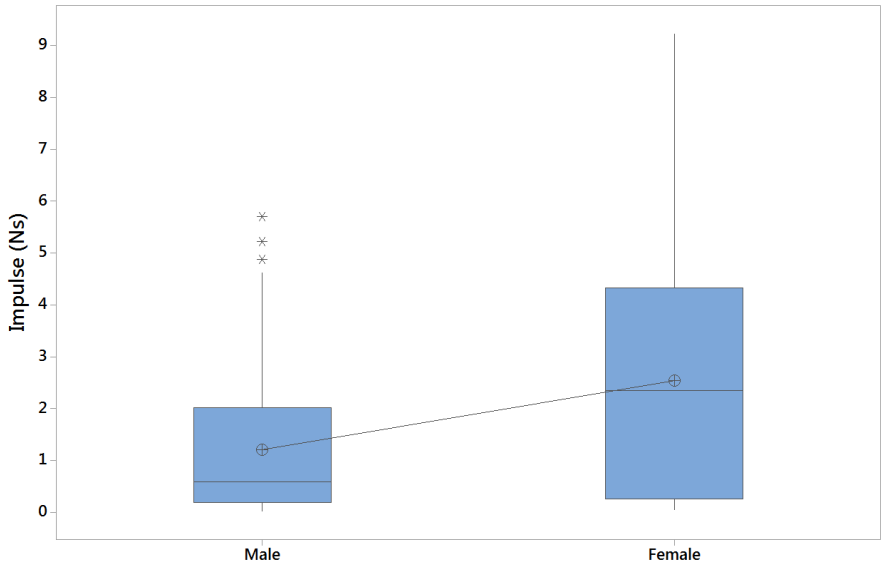

Figure 37. Comparison of texting impulse between genders.

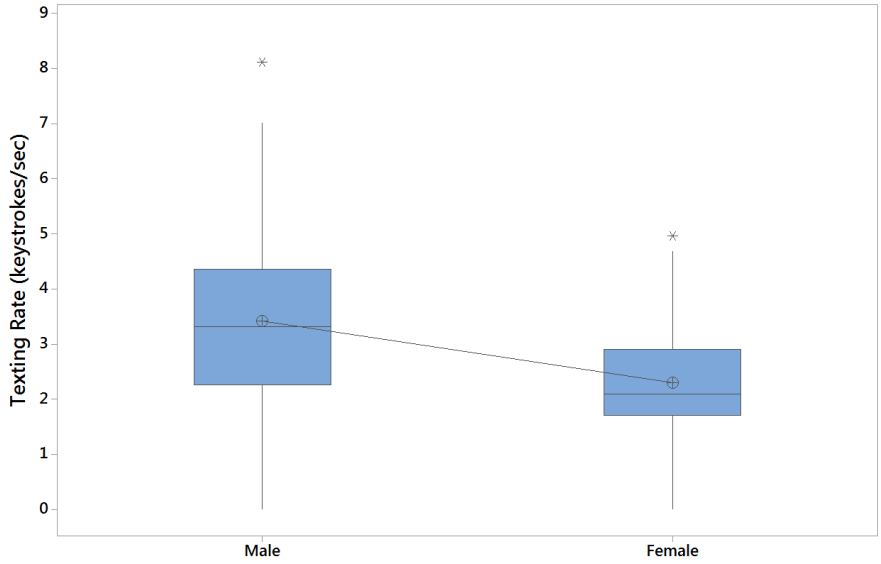

Figure 38. Comparison of texting rate between genders.

Net joint torques were investigated and was found to be larger for females in both the IP and MCP joints ($p = 0.000$) (Figure 39 - Figure 40). Females were found to have larger IP angles on sensors located on the opposite side of the cell phone from their palm

and were also found to have smaller MCP abduction and flexion angles for all but sensor 2.

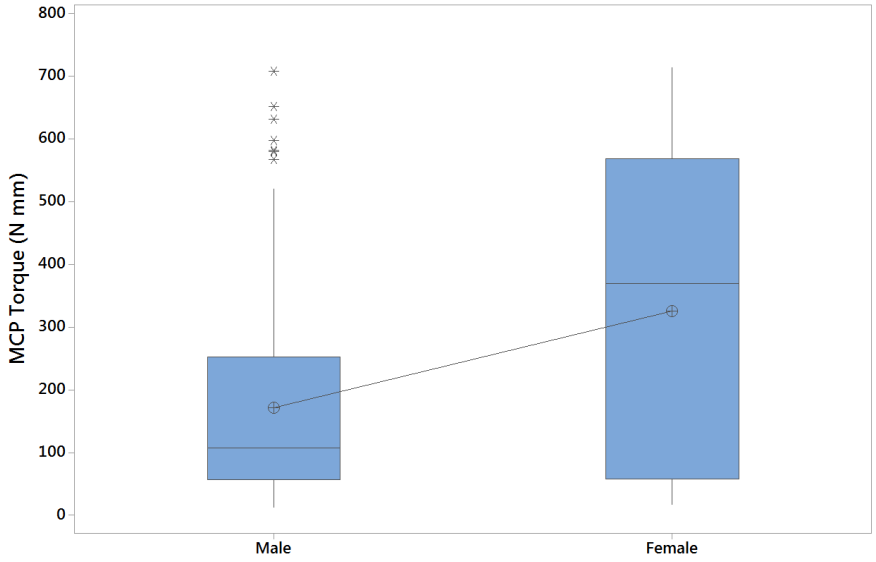

Figure 39. Comparison of MCP joint torque between genders.

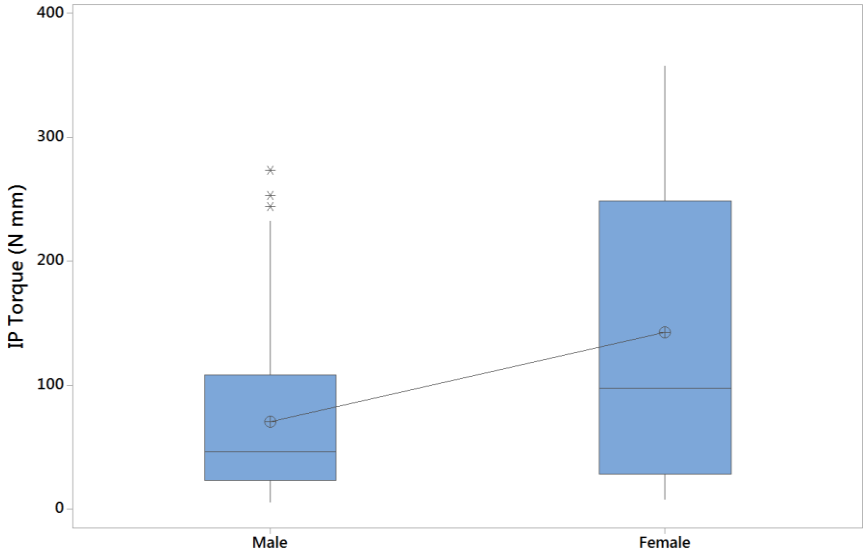

Figure 40. Comparison of IP joint torque between genders.

1.18 Phone Stability

A supplementary analysis of the data collected in this study was completed to investigate phone stability. Phone stability was interpreted as the mean variance in roll, pitch and yaw angles of the cell phone, and was found to have significant differences when comparing the same groups in the primary analysis of this study. In this study, based on the local coordinate system of the cell phone, roll, pitch and yaw are the rotation about the horizontal, longitudinal and normal axes, respectively (Figure 26).

When comparing one and two-handed texting, significantly more variance in pitch occurred during one-handed texting (p=0.000) (Figure 41). Therefore, the cell phone titled more side-to-side, about the y-axis, while texting one-handed.

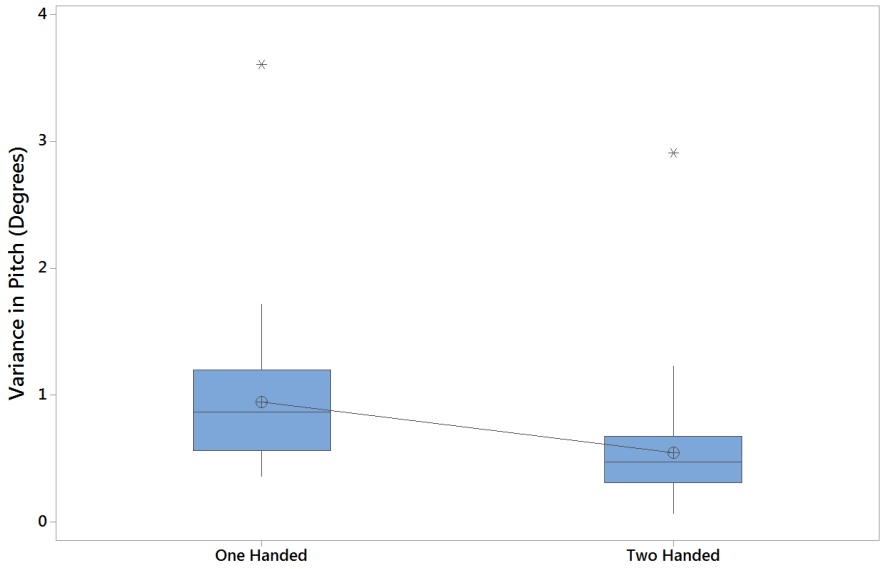

Figure 41. Comparison of the variance in pitch of the cell phone during one and two-handed texting.

Noticeable difference in variance of roll angles was found when comparing genders, during one-handed texting. Females experienced significantly larger variance in roll, meaning more tilting of the cell phone front to back (Figure 42).

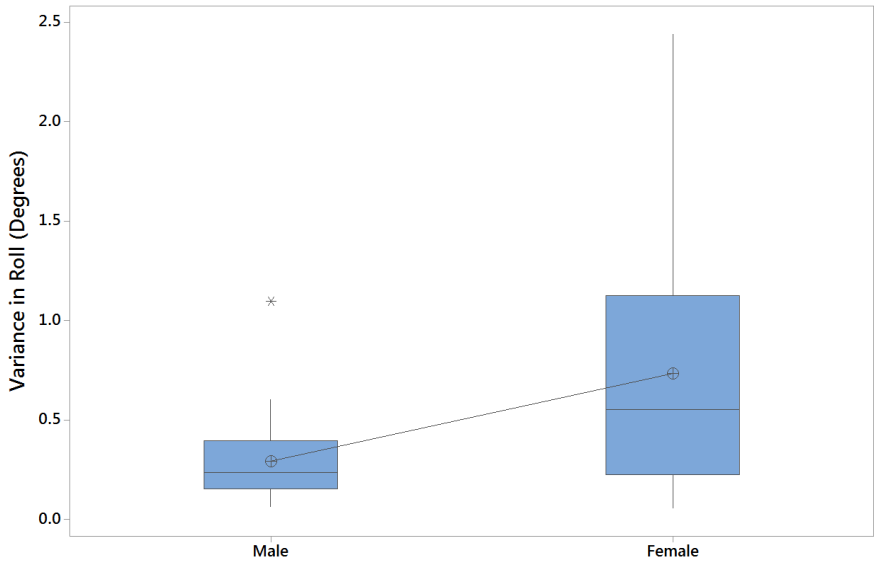

Figure 42. Comparison of variance in roll of the cell phone between genders (p = 0.008).

Variance in yaw also significantly differed between participants with and without limb loss. Participants without limb loss experienced more variance in yaw than those with limb loss (p = 0.027) (Figure 43).

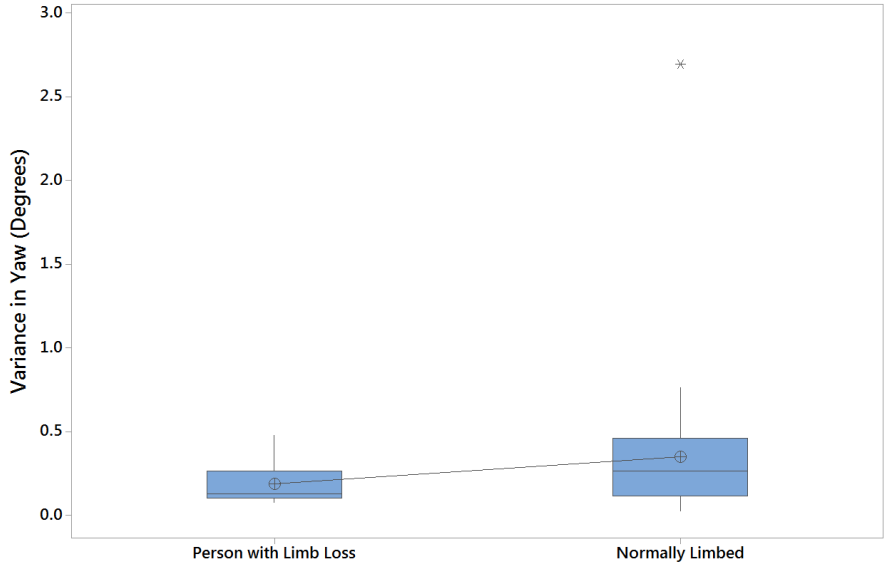

Figure 43. Comparison of the variance in yaw of the cell phone between people with and without limb loss.

1.18.1 Effects of Hand to Phone Size Ratio

Various measurements of participant's hands were taken, and listed on Survey C (Appendix C: Participant Surveys). To determine which measurement would be used to calculate hand to phone size ratio, a regression analysis found that hand breadth across the base of the thumb was the only significant hand measurement when predicting which phone was being used. With hand to phone size ratio calculated for all participants, based on the breadth of their hand across the thumb, it was found that the larger the phone was in relation to the participants hand, the less phone stability they had during texting. The variance in pitch of the phone (rotation about the y-axis of the cell phone) increased significantly as hand to phone size ratio increased. This trend was seen in both normally limbed participants, for both one and two-handed texting (Figure 44), as well as for participants with limb loss (Figure 45).

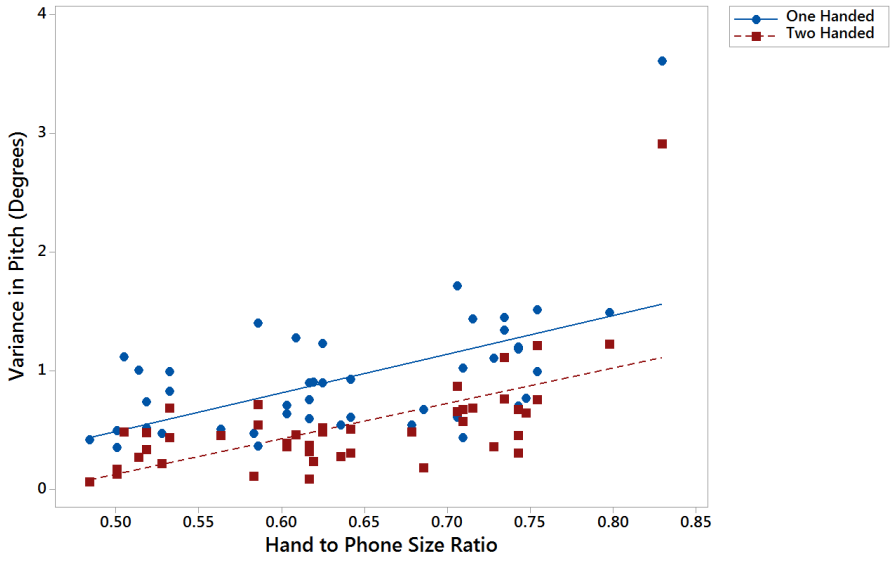

Figure 44. Correlation of hand to phone size ratio and variance in pitch, $R^2 = 0.30$ (one-handed), $R^2 = 0.31$ (two-handed).

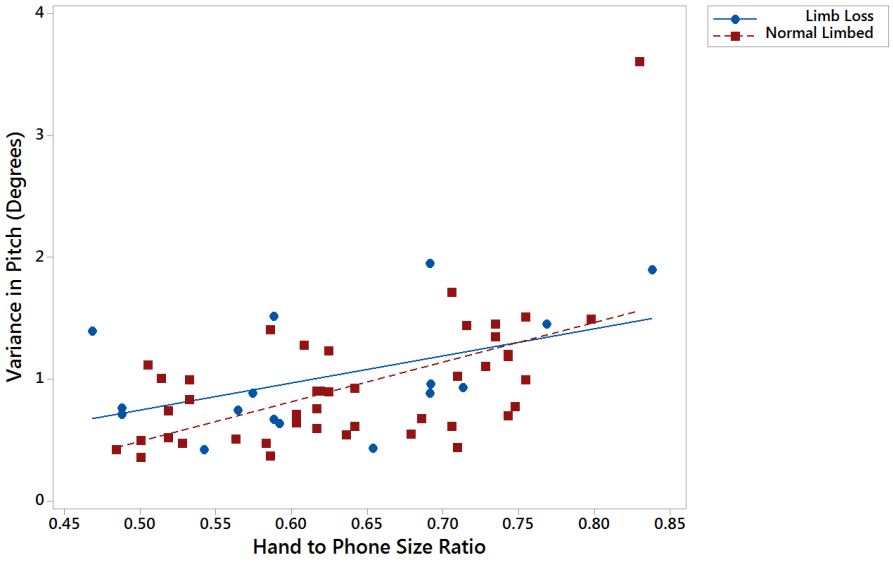

Figure 45. Correlation of hand to phone size ration and variance in pitch, R^2 = 30.35% (normally limbed), R^2 = 23.94% (participants with limb loss).

Discussion

The majority of hypotheses made prior to completing the work in this study were rejected. It was hypothesized that one-handed texting would result in higher contact forces on the cell phone screen, however it was found that larger contact forces were experienced during two-handed texting. Although there were differences found in contact forces during one and two-handed texting, they were not significant enough to lead to significantly larger joint torques.

It was hypothesized correctly, that participants with limb loss would have no significant difference in texting forces compared to normally-limbed participants. It was also expected that people with limb loss would experience longer muscle activation duration than normally limbed participants, however there was no significant difference found.

Hand to phone size ratio was expected to influence outcome measures in all participants, with joint loads predicted to increase with hand to phone size ratio. Although it was seen in all participants, the only outcome measure that showed correlation to hand to phone size ratio was phone stability, where the phone became less stable as phone size became larger in relation to the person's hand.

1.19 Strengths and Weaknesses of Study

One of the main weaknesses in this study was the small sample size compared to the large number of variables being analyzed. The large difference in size of the normally limbed group compared to the group with amputations, as well as the large number of variables, made it difficult to complete thorough statistical analyses. Moreover, the

extensive amount of variables made it difficult to develop unbiased regression models due to the limited number of variables that could be used. Consideration was made for many variables that have an effect on texting, however it was difficult to not only capture all of the variables at play, but also to control them. Although an extensive amount of information was collected during this study, focus was made only on a small list of variables to simplify the analysis.

A key strength of this study was the novel design of the texting force instrumentation. Placing sensors on the screen of the phone, compared to attaching it to the tip of the thumb, significantly reduced the amount of noise and increased the accuracy of the results. Moreover, this instrumentation method allowed for measurement of approximate force values that occur on capacitive touchscreen cell phones, which is data that has been neglected in previous studies or assumed to be zero. Although the force sensor layout was a strength of this study, it was also a weakness, as it was not possible to control how accurately the sensors were hit. Keystrokes that occurred on the sensors off-center, may have had reduced accuracy, therefore affecting the results of this study. To address this, an improved method for measuring texting forces in the future would be to use pressure sensitive screens with pressure mapping software, which is now available in some cell phone models. Using this method will not only improve force measurement, but would also allow for visual and haptic feedback, which was limited in this study. Allowing for visual and haptic feedback may improve natural texting dynamics in future studies.

The force instrumentation may have had a negative effect on results, as the associated wires offset the center of mass of the Samsung Note. The large screen size, coupled with the weight of the force sensor wires increased the difficulty to balance the

Note cell phone when texting one-handed. Although it was attempted to relieve the weight of the wires off the cell phone during the texting trials, some participants commented that it was noticeable for the Note, but not for the iPhone or Samsung Galaxy, due to their smaller dimensions.

Common errors that are experienced when using motion capture systems exist in this study. Marker placement and skin motion artifacts may have negatively affected the results. Particularly with hand movement, skin motion artifacts are known to vary significantly, however they have been proven to be within reasonable standards for completing clinical research studies using non-invasive motion tracking systems (Kuo et al., 2003). Due to complex and small movements of the hand, it was also difficult to capture the entire marker set without experiencing marker trajectory gaps, or makers falling off. Proper procedures for gap filling and calibration were followed to address these issues, however did not eliminate the possibility of their negative effect on the results in this study.

Oversimplification of thumb joint kinematic descriptions may have led to inaccurate transformation of thumb tip forces to joint torques (Valero-Cuevas, 2003). For the analysis in this study, it was assumed that the thumb is a rigid body structure with simplified mechanical joint descriptions. Soft tissue structures in articulating joints act as low friction bearings and distribute contact forces, therefore are not rigid connections and were neglected (Bartel et al., 2006). Isolating internal joint forces and torques from the opposition applied by tendons and muscles is a complex task that is outside the scope of this study. With inherent modelling errors due to various anatomical parameters, it was decided to follow common practice in biomechanics by finding net joint torques.

Results from the EMG portion of this study may have been negatively affected by common errors. Particularly the myoelectric signals from the FPL were very minimal and difficult to analyze. The FPL is a very deep subcutaneous muscle, making it difficult to acquire accurate myoelectric signals. Although it has been proven that the FPL is negatively affected by texting (Inal et al., 2015), it is suggested that future texting studies using EMG focus on other key muscles involved with texting.

1.20 One-Handed vs. Two-Handed Texting

One-handed texting raises more concern for negative musculoskeletal effects than two-handed texting. Thumb speed and APB muscle activation are significantly higher during one-handed texting, while having a significantly smaller texting rate. Therefore, texting with one hand can be interpreted as an inefficient way of texting, as there is an increased effort with less outcome. However, it should be noted that texting rate was measured in this study including keystrokes completed by both dominant and non-dominant thumbs during two-handed texting. For future studies, motion capture data could be used to determine which thumb hit the center sensor and allow for direct comparison of texting rate of only the dominant hand.

Increased APB muscle activity may have occurred as a result of less phone stability. Reaching to awkward positions to successfully text one-handed, as well as exerting larger APB muscles forces, is believed to be the cause of lower texting forces. Although more effort was made during one-handed texting, two-handed texting resulted in significantly more phone stability. The results found when comparing one and two-handed texting were supportive of previous findings (Trudeau et al., 2016).

1.21 Gender Differences

Results found in this study when comparing genders are not reflective of results found in previous studies. Other studies have suggested that females text with greater thumb abduction angles, thumb speed and contact forces (Alavi, 2015; Gold, 2012; Sharan, 2012). The results in this study suggest the opposite. This may be due to differences in instrumentation, as well as the type of phone that was being used. However, based on the results in this study, females were found to have larger torque values in both the IP and MCP joints. This result was unexpected, since females had significantly smaller hands, and smaller texting forces compared to males. Larger joint torques in females may have occurred due to shear forces that were not measured or considered in the model due to instrumentation limitations.

1.22 Effects of Having Limb Loss

Texting rates and IP joint angles were both smaller for people with limb loss. Texting at a slower rates with altered joint movement may be reflective of possible musculoskeletal symptoms. This is a reasonable assumption as both Phalen and Finkelstein test results were positive for all but one participant with an amputation. This is also supported by the reported higher pain scale values during both texting and rest, by those with limb loss. Regardless of increased pain, people with an amputation did have increased phone stability, which could be interpreted as better coordination.

The strength of the regression analysis for predicting one-handed texting was proven when entering data from participants with limb loss into the model. Multiple lines of data per phone, pattern, and sensor were entered, all returning correct results, that they were in

fact texting one-handed. Concern exists for those with limb loss who use texting as a primary form of communication, as they are subject to the greater risk of texting one-handed all of the time. Approximately 62% of normally limbed participants reported that they text one-handed less than half of the time, where 50% of those people support their cell phone in some way when texting one-handed. People with an upper limb amputation, especially those with smaller hand size, should consider alternative texting methods to avoid possible risks.

Conclusion

1.23 Summary

The motivation for this study had been the continuing growth of concern for the physiological risks associated with texting. Previously existing research that investigated this concern was not only minimal, but did not capture the entire dynamic activity of texting. This project focused on using improved instrumentation methods to investigate further the effects of texting while comparing one and two-handed texting, people with and without amputation, as well as observe the effects of hand to phone size ratio.

This study provided evidence that texting one-handed as well as having a smaller hand size, increases the concern for negative musculoskeletal symptoms. One-handed texting resulted in higher thumb speed, decreased phone stability and higher muscle activity. Inherently smaller hand size, particularly seen in females, also resulted in decreased phone stability, especially as the size of the phone increased. These results raise concern for people with upper limb amputations, as they only text one-handed, while already experiencing higher pain levels, lower texting rates and show more symptoms for musculoskeletal injuries.

1.24 Recommendations

To improve the efficiency of how the data collected from this experiment could be used, the protocol could be improved in a number of ways. Since there were no significant differences found, completing long texting patterns can be removed completely. Instrumentation configuration time could also be reduced by purchasing enough phone sensors to instrument all 3 phones simultaneously, also reducing any associated error

caused by switching phones. With regards to motion capture, since only variables involving the thumb were used, the marker set can be drastically reduced and the capture volume can be calibrated more closely to the hand.

1.25 Future Work

Investigating all of the variables that have an effect on texting, and how they interact is an ongoing process that needs continuous dedication. Building on this study by incorporating a larger sample size with more of the variables collected in the data set, as well as in the participant surveys is required. Particularly relating results back to people's level of experience with texting. Otherwise, developing an experimental design that effectively isolates such variables is needed. The objectives of this study were met through the comparison of key groups, and significant results were found. The anonymous data collected will be made available to the IBME for further investigation of other variables that may have an effect on texting.

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Appendix A: Force Sensors

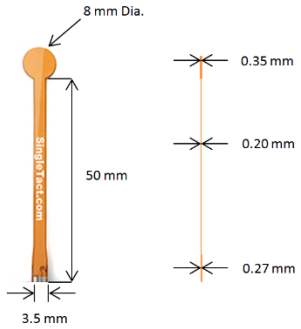

Figure 46. SingleTact sensor schematic.

Table 5 SingleTact Sensor Performance

Parameter	**Value**
Type	Capacitive
Force Range	0 – 10N
Signal to noise ratio	500:1
Force resolution	< 0.2 % Full Scale (FS)
Typical repeatability error	< 1.0 % (1 sigma of FS)
Operating temperature	-40°C to 200°C
Temperature sensitivity	Up to 0.2% / °C
Linearity error	< 0.2%
Drift	< 2% per logarithmic time scale
Hysteresis	< 0.4%
Response time	< 1 ms
Contact surface material	Polymide
Sensor thickness	0.35 mm
Typical baseline capacitance	135 pF
Typical capacitance change	8 pF

Table 6 SingleTact Electrical Parameters

Parameter	**Value**
Supply Voltage Vcc	3.7 – 12 V
Input current	2.5 mA running at 3MHz
IO voltage	3.3 V
I^2C clock frequency	100 KHz or 400 KHz
I^2C bus level	3 – 5 V
Analog out	0.5 –1.5 V
Permitted analog output load	> 5 KΩ
Frame Sync level	3.3 V CMOS output
Update rate	> 300 Hz
Electronics operating temperature	-40°C to 85°C
Weight	Sensor 0.23g/ Electronics 1.6g

Appendix B: Informed Consent

UNIVERSITY OF NEW BRUNSWICK

INSTITUTE OF BIOMEDICAL ENGINEERING

INFORMED CONSENT

An Inverse Dynamic Analysis of One Handed Texting

Primary Investigators

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Approval

This project has been reviewed by the Research Ethics Board and is on file as REB #2016-058.

Purpose

The purpose of this data collection is to study the internal forces in the hand and wrist that occur when texting. Findings may highlight potential risk factors for mobile device users.

Procedure

As a participant in this study, you will be required to attend one session of texting trials for the purpose of data collection. During the session, you will first be asked to complete a survey requesting personal information such as age, sex and handedness. You will also be asked to estimate the number of messages you send on your mobile phone per day. Measurements of your hand will be taken. Simple, commonly used physical exams will be used to assess your range of motion and strength, as well as evaluate any pre-existing injuries. EMG electrodes will be secured to your hand and forearm. Reflective markers for motion capture will also be placed on landmarks on your upper arm and trunk. With the use of various sized cell phones, provided by the experimenter, you will be asked to type specific texting patterns on the phone. All force, EMG and motion data will be recorded and processed later.

Withdrawal

Participation is strictly voluntary, with no obligation to complete the experiment. You may withdraw at any point and request the destruction of your data without consequence.

Feedback

Comments, concerns, questions, and other feedback may be sent to any of the investigators listed above. You may also request information regarding the final outcome of the study, i.e., any conclusions, presentations, and publications, by contacting the investigators.

If you wish to contact someone who is not involved with this project with concerns, questions, or feedback, you may do so with the following people:

Dr. Kevin Englehart
Director, Institute of Biomedical Engineering
kengleha@unb.ca
453–4966

Dr. Jon Sensinger
Associate Director, Institute of Biomedical Engineering
j.sensinger@unb.ca
458–7094

Risks

Surface EMG recordings and motion capture methods are a standard procedure at the Institute of Biomedical Engineering, with no known risks of injury or discomfort. A slight skin impression may be made by the electrodes or markers, due to their snug fit or adhesiveness, however this will dissipate naturally in a short amount of time. Some people may have skin iritation in the areas where the adhesive contacts the skin.

Potential Benefits

Participants will receive no inducements or benefits for their involvement in this experiment.

Confidentiality

Your data will remain anonymous for all publications and presentations. Presentations of individual data may be referenced using a subject number that is not publicly connected with your identity.

Consent

I have read and understood the above information and do hereby agree to participate in this study and consent to the use of data recorded during this experiment for scientific research purposes as stated above. I understand that my identity will remain confidential, and that my anonymized data may be shared amongst the investigators and their collaborators as part of their research program. I understand that my decision whether or not to participate in this experiment will not affect my academic standing, nor any services I may receive from the Atlantic Clinic for Upper Limb Prosthetics. I can withdraw from this study at any time with no consequence. I agree that all my questions and concerns have been addressed in a satisfactory manner.

Participant: _____ Signature: _____ Date: _____

Guardian : _____ Signature : _____ Date : _____

Investigator: _____ Signature: _____ Date: _____

Appendix C: Participant Surveys

SURVEY A	CONFIDENTIAL	PARTICIPANT:_____

Repetitive Strain Injury due to One Handed Texting
Pain/Activity Survey

The purpose of this questionnaire is to assess the day to day activities of the people who are participating in this study. It is quite short and simple, and should take no more than 10 to 15 minutes to complete.

SECTION A – PARTICIPANT INFORMATION			
1.1 Gender	**1.2 Age**	**1.3 Height**	**1.4 Weight**
1.5 Please indicate the number of years you have owned a cell phone with text messaging features?			
1.6 On average, how many SMS text messages do you send on your mobile phone per day? Please select one of the following, or enter the known average value if available.			
☐ Light texter (0 – 50 per day) ☐ Light – Medium texter (50 – 100 per day) ☐ Medium – Heavy texter (100 – 150 per day) ☐ Heavy (150 +)		**Average number of SMS text messages sent on your mobile phone per day, if available:**	
1.7 On average, how many non SMS text messages do you send on your mobile phone per day? This may include, but not be limited to, iMessage, Facebook Messenger, or WhatsApp. Please select one of the following, or enter the known average value if available.			
☐ Light texter (0 – 50 per day) ☐ Light – Medium texter (50 – 100 per day) ☐ Medium – Heavy texter (100 – 150 per day) ☐ Heavy (150 +)		**Average number of non SMS text messages sent on your mobile phone per day, if available:**	
1.8 What model and type of mobile phone do you use currently?			
1.9 Please indicate your side of limb loss.			
☐ Right ☐ Left			
1.10 Please select only one type of limb loss:			
☐ Congenital - Limb deficiency at birth ☐ Traumatic - Limb deficiency at the time of an accident or event ☐ Medical - Limb deficiency after birth, possibly from disease			
1.11 Please indicate the year when you had your amputation. (If congenital, please enter year of birth)			
1.12 Please indicate your dominant side prior to amputation. (If congenital, do not answer)			
☐ Right ☐ Left			

1.13 On average, how often do you use a prosthesis? Please select one of the following:

- ☐ Never
- ☐ Occasionally (1-3 times/week)
- ☐ Regularly (4-6 times/week)
- ☐ Daily

1.14 If you ever support your mobile phone while texting using your prosthesis or other methods, please explain.

SECTION B – ACTIVITY SURVEY

2.1 On average, how often do you use a desktop, laptop or tablet computer?

- ☐ Never
- ☐ Occasionally (1-3 times/week)
- ☐ Regularly (4-6 times/week)
- ☐ Daily

2.2 For each of the following activities please indicate whether you participate in each of the activities regularly, occasionally or never. If you do not take part in a particular activity, please select "never".

Team activities	Never	Occasionally	Regularly
Computer Gaming			
Console Gaming			
Handheld Gaming			
Musical Instruments			
Golf			
Yoga/Gymnastics/Fitness			
Needle Craft (Knitting, embroidery)			
Seasonal Team Sports (Please specify)			
If other please specify:			

2.3 Please indicate your current job/occupation.

- ☐ Student
- ☐ Not employed
- ☐ Employed
- ☐ Student and employed

If employed please indicate your job title in the box below:

2.4 If employed, how many hours per week do you work?

2.5 If your current job or occupation involves completing repetitive tasks with your hands, please specify.

SECTION C – PAIN SURVEY

3.1 Please identify the intensity of any pain you may experience at the specified locations when relaxed:

No pain | Mid. annoying Pain | Nagging, uncomfortable, troublesome pain | Distressing pain | Intense, dreadful, horrible pain | Worst possible, unbeatable excruciating pain

Pain Scale	0	1	2	3	4	5	6	7	8	9	10
Thumb											
Wrist											
Forearm											
Elbow											
Shoulder											
Neck											
Back											

3.2 Please identify the intensity of any pain you may experience at the specified locations when texting and/or gaming:

Pain Scale	0	1	2	3	4	5	6	7	8	9	10
Thumb											
Wrist											
Forearm											
Elbow											
Shoulder											
Neck											
Back											

3.3 If you experience any other pain in your upper body that was not listed above, please explain.

3.4 If you experience any phantom pain or sensations, please explain.

3.4 Please indicate the time when your pain is the most bothersome (1), second most bothersome (2), and least bothersome (3).

1. _____
2. _____
3. _____

Examples:
During Team Sport
During Individual Recreational Activities
While at work/school
While relaxing
When I first wake up in the morning
Other

If other, please specify: _____

3.5 Please indicate the location of your most bothersome (1), second most bothersome (2) and least bothersome (3) pain.

1. _____
2. _____
3. _____

Location of Pain:
Thumb
Wrist
Forearm
Elbow
Shoulder
Neck
Back

3.6 Have you ever sought medical care for any of the pain described in this survey?

☐ Yes ☐ No

If yes, please explain: _____

SURVEY B	CONFIDENTIAL	PARTICIPANT:_____

Repetitive Strain Injury due to One Handed Texting
Pain/Activity Survey

The purpose of this questionnaire is to assess the day to day activities of the people who are participating in this study. It is quite short and simple, and should take no more than 10 to 15 minutes to complete.

SECTION A – PARTICIPANT INFORMATION			
1.1 Gender	**1.2 Age**	**1.3 Height**	**1.4 Weight**

1.5 Please indicate the number of years you have owned a cell phone with text messaging features?

1.6 On average, how many SMS text messages do you send on your mobile phone per day? Please select one of the following, or enter the known average value if available.	
☐ Light texter (0 – 50 per day) ☐ Light – Medium texter (50 – 100 per day) ☐ Medium – Heavy texter (100 – 150 per day) ☐ Heavy (150 +)	**Average number of SMS text messages sent on your mobile phone per day, if available:**

1.7 On average, how many non SMS text messages do you send on your mobile phone per day? This may include, but not be limited to, iMessage, Facebook Messenger, or WhatsApp. Please select one of the following, or enter the known average value if available.	
☐ Light texter (0 – 50 per day) ☐ Light – Medium texter (50 – 100 per day) ☐ Medium – Heavy texter (100 – 150 per day) ☐ Heavy (150 +)	**Average number of non SMS text messages sent on your mobile per day, if available:**

1.8 What model and type of mobile phone do you use currently?

1.9 Please indicate your handedness.
☐ Right ☐ Left

1.10 On average, what percentage of all messages sent do you complete one handed.
☐ 0 – 25 % (I mostly text two handed, where I use both hands for mobile phone support and/or typing) ☐ 25 – 50 % (I text one handed occasionally) ☐ 50 – 75 % (I text one handed often) ☐ 75 – 100% (I text one handed very often)

1.11 When texting one handed (using the same hand to hold the phone while typing) approximately what percentage of messages typed are completed using your dominant hand?
☐ 0 – 25 % (I mostly text one handed using my non-dominant hand) ☐ 25 – 50 % (I occasionally use my dominant hand to text one handed) ☐ 50 – 75 % (I often use my dominant hand to text one handed) ☐ 75 – 100% (I primarily use my dominant hand to text one handed)

1.12 If you ever support your mobile phone while texting, please explain. (i.e. Using your opposite hand to support the phone, or resting the phone on a table while typing.)

SECTION B – ACTIVITY SURVEY

2.1 On average, how often do you use a desktop, laptop or tablet computer?

- ☐ Never
- ☐ Occasionally (1-3 times/week)
- ☐ Regularly (4-6 times/week)
- ☐ Daily

2.2 For each of the following activities please indicate whether you participate in each of the activities regularly, occasionally or never. If you do not take part in a particular activity, please select "never".

Team activities	Never	Occasionally	Regularly
Computer Gaming			
Console Gaming			
Handheld Gaming			
Musical Instruments			
Golf			
Yoga/Gymnastics/Fitness			
Needle Craft (Knitting, embroidery)			
Seasonal Team Sports (Please specify)			
If other please specify:			

2.3 Please indicate your current job/occupation.

- ☐ Student
- ☐ Not employed
- ☐ Employed
- ☐ Student and employed

If employed please indicate your job title in the box below:

2.4 If employed, how many hours per week do you work?

2.5 If your current job or occupation involves completing repetitive tasks with your hands, please specify.

SECTION C – PAIN SURVEY

Scale 0 1 2 3 4 5 6 7 8 9 10

No pain | Mid. annoying Pain | Nagging, uncomfortable, troublesome pain | Distressing pain | Intense, dreadful, horrible pain | Worst possible, unbeatable excruciating pain

3.1 Please identify the intensity of any pain you may experience on your dominant side, at the specified locations when relaxed:

Pain Scale	0	1	2	3	4	5	6	7	8	9	10
Thumb											
Wrist											
Forearm											
Elbow											
Shoulder											
Neck											
Back											

3.2 Please identify the intensity of any pain you may experience on your dominant side, at the specified locations when texting and/or gaming:

Pain Scale	0	1	2	3	4	5	6	7	8	9	10
Thumb											
Wrist											
Forearm											
Elbow											
Shoulder											
Neck											
Back											

3.3 If you experience any other pain in your upper body on your dominant side that was not listed above, please explain.

SECTION C – PAIN SURVEY

Scale 0 1 2 3 4 5 6 7 8 9 10

No pain | Mid. annoying Pain | Nagging, uncomfortable, troublesome pain | Distressing pain | Intense, dreadful, horrible pain | Worst possible, unbeatable excruciating pain

3.4 Please identify the intensity of any pain you may experience on your non dominant side, at the specified locations when relaxed:

Pain Scale	0	1	2	3	4	5	6	7	8	9	10
Thumb											
Wrist											
Forearm											
Elbow											
Shoulder											
Neck											
Back											

3.5 Please identify the intensity of any pain you may experience on your non dominant side, at the specified locations when texting and/or gaming:

Pain Scale	0	1	2	3	4	5	6	7	8	9	10
Thumb											
Wrist											
Forearm											
Elbow											
Shoulder											
Neck											
Back											

3.6 If you experience any other pain in your upper body on your non dominant side that was not listed above, please explain.

3.7 Please indicate the time when your pain is the most bothersome (1), second most bothersome (2), and least bothersome (3).

1. _____
2. _____
3. _____

Examples:
During Team Sport
During Individual Recreational Activities
While at work/school
While relaxing
When I first wake up in the morning
Other

If other, please specify: _____

3.8 Please indicate the location of your most bothersome (1), second most bothersome (2) and least bothersome (3) pain.

1. _____
2. _____
3. _____

Location of Pain:
Thumb
Wrist
Forearm
Elbow
Shoulder
Neck
Back

3.9 Have you ever sought medical care for any of the pain described in this survey?

☐ Yes ☐ No

If yes, please explain: _____

SURVEY C	CONFIDENTIAL	PARTICIPANT:_____

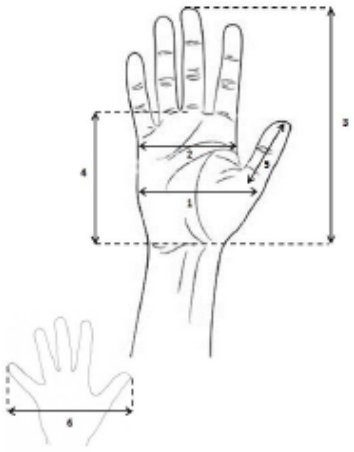
Repetitive Strain Injury due to One Handed Texting
Function/Anthropometric Evaluation

SECTION A – FUNCTION EVALUATION

For the following examinations, please indicate if you experienced any pain, tingling or numbness.

Test	Pain	Tingling	Numbness	Comments
Finkelstein	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	
Phalen	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	
Dynamometer _____ lb	☐ Yes ☐ No	☐ Yes ☐ No	☐ Yes ☐ No	

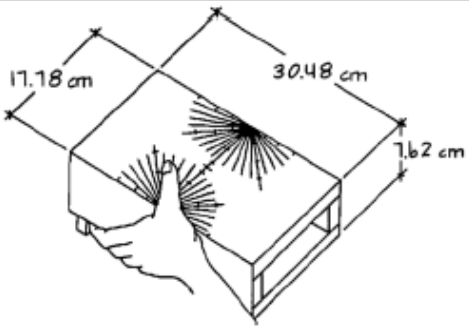
SECTION B – ANTHROPOMETRIC MEASURMENTS



	Dimension	Units (mm)
1	Hand Breadth (across thumb)	
2	Hand Breadth (metacarpal)	
3	Hand Length	
4	Palm Length	
5	Thumb Length	
6	Maximum Spread	

Comments:

SECTION C – RANGE OF MOTION MEASUREMENT



Gilbert, 1988

	Measurement	Units (mm)
1	Resting Thumb Angle	
2	Thumb Reach at 0°	
3	Thumb Reach at 45°	
4	Thumb Reach at 90°	
5	Maximum Thumb Angle	

Comments:

Appendix E: Complete Marker Set

1. FRHD – Front Head
2. LTHD – Left Head
3. RTHD – Right Head
4. C7 – 7th Cervical Vertebrae
5. SHO – Acromion Process
6. UPA – Mid Humorous
7. ELBL – Lateral Epicondyle
8. LOA – Mid Ulna
9. RAD – Radial Styloid Process
10. ULNA – Ulnar Styloid Process
11. CMC – Carpometacarpal Joint
12. MET1 – Mid Fist Metacarpal Segment
13. MCPM – Medial Side of the First Metacarpophalangeal Joint
14. MCPL - Lateral Side of the First Metacarpophalangeal Joint
15. PPHA – Mid First Proximal Phalanx
16. IPM – Medial Side of the First Interphalangeal Joint
17. IPL – Lateral Side of the First Interphalangeal Joint
18. DPHA – Distal End of the Distal Phalanx
19. MET2 – Second Metacarpophalangeal Joint
20. DSUR1 – Dorsal Surface of the Hand Cluster
21. DSUR2 - Dorsal Surface of the Hand Cluster
22. DSUR3 - Dorsal Surface of the Hand Cluster
23. RCP – Right Cell Phone Cluster
24. LCP – Left Cell Phone Cluster
25. CCP – Center Cell Phone Cluster
26. RHIP – Right Hip
27. LHIP – Left Hip

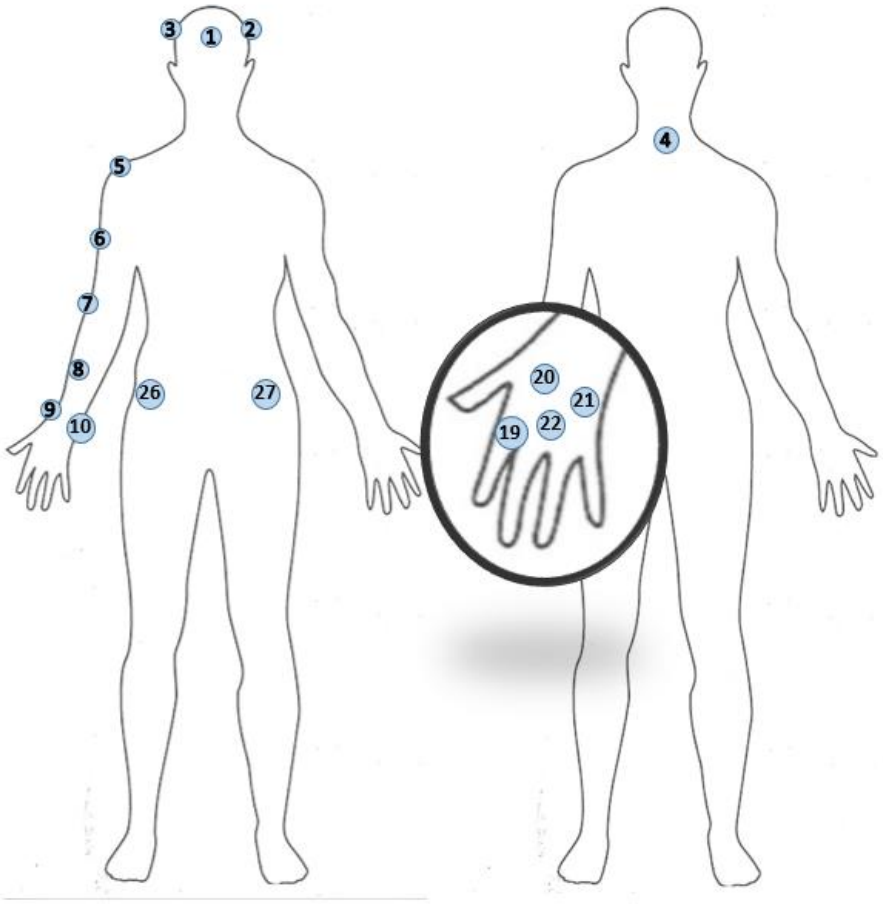


Figure 47. Marker locations on (Left) front view and (Right) back view.

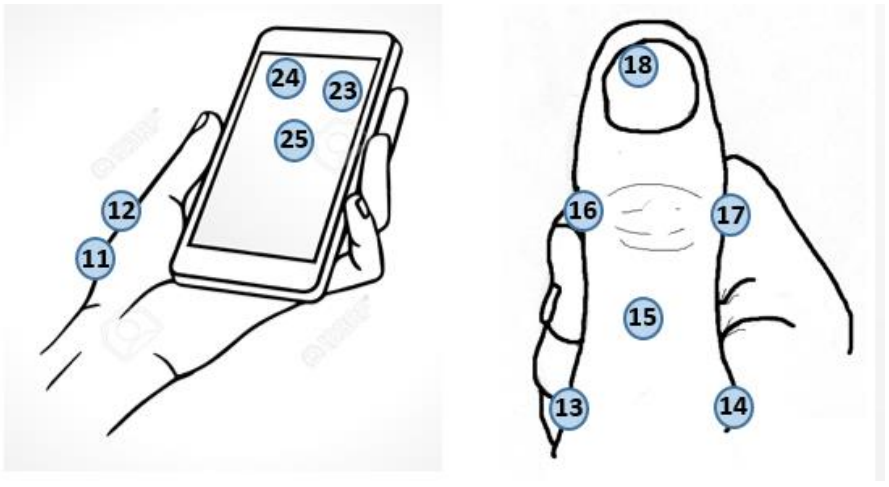
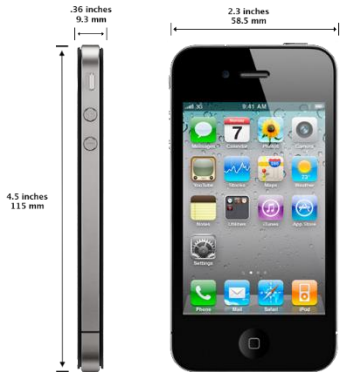


Figure 48. Marker locations on (Left) the hand and cell phone and (Right) the thumb.

iPhone 4	Samsung Galaxy 3	Samsung Note
		
Width: 58.5 mm Height: 115 mm Thickness: 9.3 mm	Width: 70.6 mm Height: 136.6 mm Thickness: 8.6 mm	Width: 82.95 mm Height: 146.9 mm Thickness: 9.65 mm
*All three phones were controlled at the same weight of 137g.		

Appendix G: Activities of Daily Living

Participant	Limb Loss	Employment	Years Owning Cell Phone	SMS Messages Per Day*	Technology use (i.e. Desktop/Laptop/Tablet)**	Regular or Daily Activity
1	No	Student	7	1	4	--
2	No	Student	7	2	4	Console Gaming
3	No	Student	8	2	4	Team Sports
4	No	Student	11	1	4	Needle Craft
5	No	Student	12	2	4	Yoga/Fitness
6	No	Student	10	2	4	Yoga/Fitness, Needle Craft
7	No	Student	11	1	4	Handheld Gaming, Yoga/Fitness
8	No	Student	8	1	3	Yoga/Fitness
9	No	Student	8	2	4	Console Gaming, Yoga/Fitness, Team Sports
10	No	Student	10	1	4	Console Gaming, Team Sports
11	Yes	Student	6	1	2	Yoga/Fitness
12	No	Student	5.5	4	2	Team Sports
13	No	Part Time	6	2	4	Yoga/Fitness
14	No	Student	8	1	4	Computer and Handheld Gaming, Yoga/Fitness
15	No	Student	8	1	4	Yoga/Fitness
16	No	Part Time	7.5	1	4	Yoga/Fitness, Musical Instruments, Team Sports
17	No	Full Time	10	1	4	Yoga/Fitness
18	Yes	Unemployed	10	1	4	Needle Craft
19	Yes	Unemployed	11	3	2	--
20	Yes	Unemployed	9	3	2	Console and Handheld Gaming
21	Yes	Unemployed	22	1	4	Handheld Gaming
22	Yes	Full Time	12	1	4	Yoga/Fitness, Team Sports
23	Yes	Full Time	16	2	4	Computer, Console and Handheld Gaming Musical Instruments

* 1 = Light (0-50), 2 = Light/Medium (50 – 100), 3 = Medium/Heavy (100-150), 4 = Heavy (150+)

** 1 = Never, 2 = Occasionally, 3 = Regular, 4 = Daily

Curriculum Vitae

Candidate's full name: Rachelle Ann Bernier

Universities attended:

MScE Mechanical Engineering (2015 – 2018)
University of New Brunswick

BASc Biomedical Mechanical Engineering (2011 – 2015)
University of Ottawa

Conference Presentations:

Bernier R, Biden E, Hill W, Rickards. J, "An Inverse Dynamic Analysis of One-Handed Texting", *Association of Children's Prosthetics and Orthotics Clinic Annual Meeting*, Grand Rapids, Michigan, April 2018.

Bernier R, Biden E, Hill W, Rickards. J, "An Inverse Dynamic Analysis of One-Handed Texting", *Mechanical Engineering Graduate Student Society Conference*, Fredericton, Feb 2015 and 2016. Poster Presentations.