

# **Risks of One-Handed Texting in Upper-limb Amputees**

by

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## **Abstract**

This thesis details risks of one-handed texting and includes people with limb loss. The goal of this research is to help prevent repetitive strain injuries related to texting. People with limb loss may be more at risk due to overuse syndrome. 23 people participated in the study, seven with upper limb loss. The data were acquired using several instruments (on three phone sizes) including motion capture, thumb forces on the phone, electromyography, and surveys.

The Limb Loss group consistently reported higher pain than the control group. Wrist extension angles while texting were 14 degrees higher in the Limb Loss group. Limb Loss participants required more time to complete standardized texting patterns by as much as 1.8 seconds longer and held force sensors for longer as well. The relative risk of conditions and texting habits were found to be significantly higher in the Limb Loss group. Texting pattern completion times decreased when the control group texted two-handed (especially on larger phones), an option the Limb Loss group does not possess.

Higher thumb forces added time to completing texting patterns. Large hand sizes showed an advantage while texting in a few ways such as: lowering thumb applied forces, completing texting patterns faster, and reaching hard to reach force sensors on large phones. A larger phone size affected texting mechanics in several ways such as: increasing time required to complete patterns and an increase in muscle activation.

When possible, people with limb loss should support their phone on a surface, pay close attention to their wrist posture, use an appropriately sized phone, and make a conscious effort to apply less force to the keyboard.

## **Dedication**

To Grampie and Vivian, who taught me about resilience and love.

## **Acknowledgements**

I would like to thank Kristyn, my family, friends, and committee (Ed, Wendy, and Gobinda) for their outstanding patience, and for picking me up time and time again. I'd like to thank Rachelle Bernier for collecting the data, it wouldn't have been possible without her hard work. As well as Jeremy Rickards for his knowledge and contribution to this work. Finally, Evan Campbell for all the surgery he performed on my coding, and the rest of my IBME family for their support.

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## **Abbreviations**

ADL – Activities of daily living

AP - Adductor pollicis

APB - Abductor pollicis brevis

APL - Abductor pollicis longus

CMC - Carpometacarpal

CWTA – Canadian Wireless Telecommunications Association

DAQ – Data acquisition

DOF – Degrees of freedom

EMG –Electromyography

EPB - Extensor pollicis brevis

EPL - Extensor pollicis longus

FDI - First dorsal interosseous

FPB - Flexor pollicis brevis

FPL - Flexor pollicis longus

IBME – Institute of Biomedical Engineering

IP – Interphalangeal

MCP – Metacarpophalangeal

OP - Opponens pollicis

RSI – Repetitive strain injury

# 1. Introduction

Texting is a very popular form of communication. Texting in the context of this research refers to shorthand messaging on mobile devices. The Canadian Wireless Telecommunications Association (CWTA) reports a steady increase in data usage of 38% yearly as the popularity of smartphones continues to grow (CWTA, 2019). The average Canadian sends 50 text messages, and an additional 27 emails via mobile phones (or another internet-centric communication method) per day (Sinha, 2013) and these numbers are expected to keep increasing.

A publication by Gustafsson with 7092 participants compared survey results from texting and body part pain with a 5 year follow up survey. The survey showed that an increase in mobile texting led to an increase in long-term pain in the neck, shoulder, and hand (Gustafsson et al., 2017). This increase in long-term pain may be linked to the general population developing repetitive strain injuries (RSI).

The data used in this study was collected at the Institute of Biomedical Engineering by Rachele Bernier in 2018. Prior to the Covid-19 pandemic the intention was to add more participants to bolster the data. Due to the pandemic no extra data collection was possible. This analysis is entirely based on the existing data.

Some preliminary work has been done on the data set acquired for this research. Bernier commented on some key findings to take note of and build on for the current study. Female forces on the phones were higher, phone stability was dependant on hand size, thumb speed and muscle activation were higher during one-handed texting, and that people with limb loss reported more pain on the experiment survey.

People with upper extremity limb loss report higher pain than normally limbed people (Bernier, 2018; Hill et al., 2017; Ostlie et al., 2011). Knowing this fact allows for further studies like this one to analyze the cause. The increase in pain may be from overuse syndrome, pre-existing trauma to the musculoskeletal system, or postural differences that arise from issues associated with missing an upper limb.

The purpose of this research is to determine whether one-handed texting poses a risk to developing RSIs in unilateral upper limb amputees. By analyzing data from force sensors, motion capture, electromyography, and survey information, it will assess the differences between groups regarding risks of one-handed texting and developing texting related RSIs.

For the current study, the following hypotheses are posed:

1. Non-neutral posture is related to localized pain in the hand, arm, and neck.
2. Texting mechanics and body posture are influenced by phone size.
3. Texting mechanics and efficiency are influenced by anthropometrics and texting habits.

## **2. Literature Review**

### **2.1 Anatomy and Texting**

Reviewing hand anatomy is an important element of this research. Bones, joints, muscles, and tendons work together to complete texting tasks and it is therefore important to know how they move. They will be referenced throughout this study to

indicate where points of interest on the body are located and how they may be impacted during texting.

The hand is made up of many bones but the ones of interest here are those of the thumb used in texting (see Figure 1). Starting at the distal part of the thumb and working down to the base:

- Distal Phalanx (DP), flexes and extends, makes contact with phone keypad
- Interphalangeal Joint (IP), hinge joint, allows flexion and extension of DP
- Proximal Phalanx (PP), flexes, extends, abducts, and adducts, improves range of motion in the thumb
- Metacarpophalangeal Joint (MCP), saddle joint, allows flexion, extension, abduction, and adduction of PP
- Metacarpal (MC), rotational, improves range of motion in the thumb
- Carpometacarpal Joint (CMC), biconcave-convex saddle joint, allows movement of the thumb's metacarpal

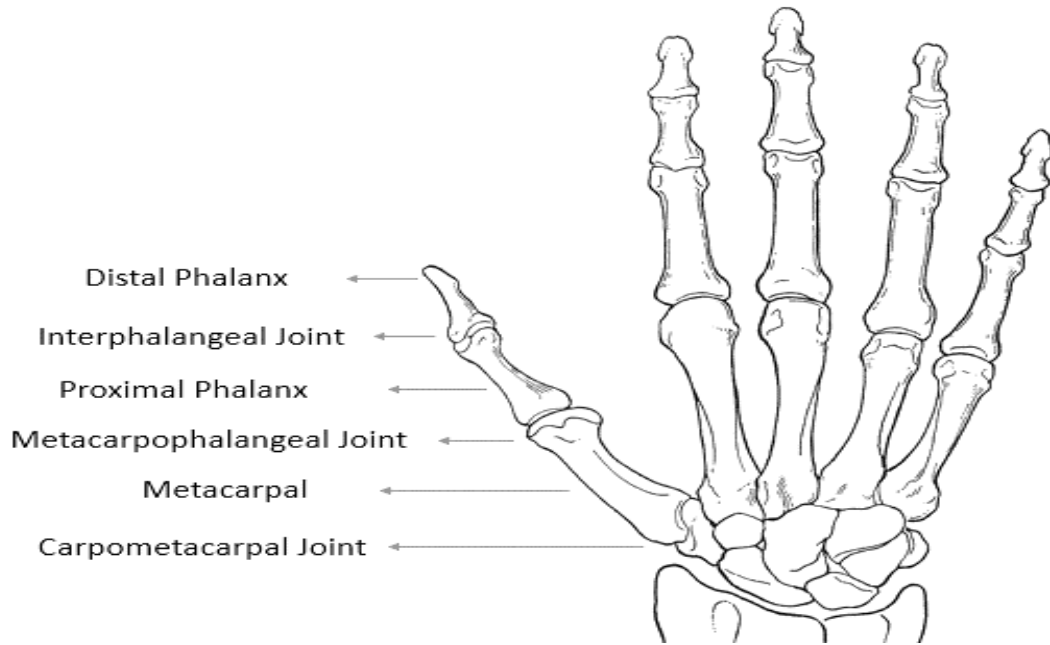


Figure 1: Thumb Bone Structure and Joints (Orthogate, 2018)

The thumb's movements are controlled by muscle-tendon pairings (see Figure 2). These muscles and tendons are often intuitively named to describe their primary movement capabilities (e.g. extensor pollicis longus extends the DP, see Figure 2). Thumb muscles are grouped into extrinsic and intrinsic muscle groups. The extrinsic muscle group are four long muscles that originate in the forearm and extend down the arm to the thumb (Okwumabua et al., 2020). These muscles include the Abductor Pollicis Longus (APL), Extensor Pollicis Brevis (EPB), Extensor Pollicis Longus (EPL), and the Flexor Pollicis Longus (FPL). The intrinsic muscle group (Thenar eminence) contains five muscles, it includes the Adductor Pollicis (transverse), Adductor Pollicis (oblique), the Flexor Pollicis Brevis (FPB), Opponens Pollicis (OP), and the Abductor Pollicis Brevis (APB) (Kapandji, 1980).

### Extrinsic thumb muscles

- a. Abductor pollicis longus
- b. Extensor pollicis brevis
- c. Extensor pollicis longus
- d. Flexor pollicis longus

### Thenar eminence

- 1. Adductor pollicis (transverse)
- 2. Adductor pollicis (oblique)
- 3. Flexor pollicis brevis
- 4. Abductor pollicis brevis
- 5. Opponens pollicis

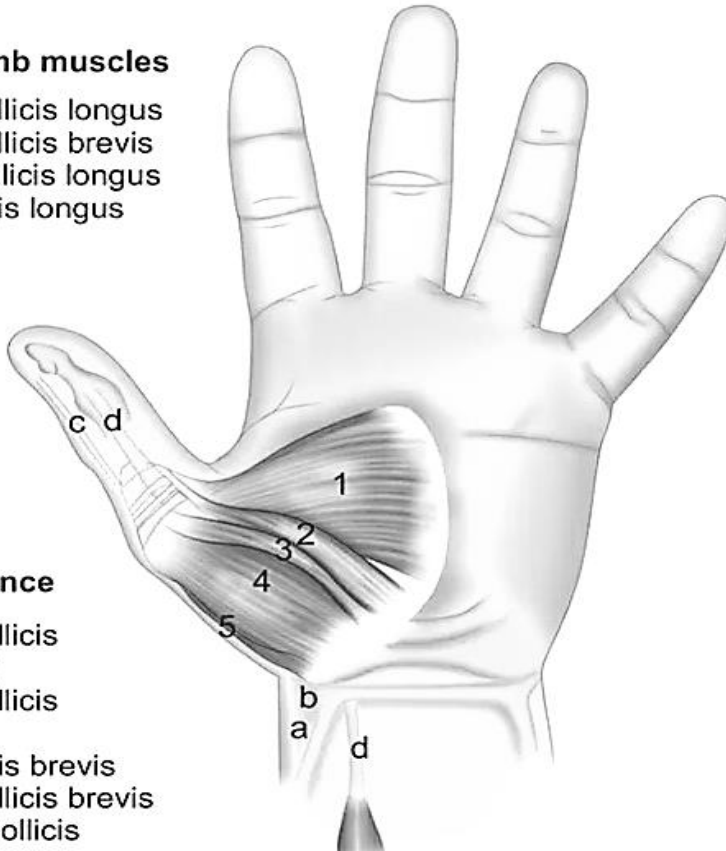


Figure 2: Thumb Muscles Palmer View (Sayeli, 2018)

The musculoskeletal system of the hand can be damaged by repetitive movements. Coupling this with abnormal posture also poses a risk (Mathiassen, 2006). There are two common repetitive strain injuries (RSIs) associated with texting, Carpal Tunnel Syndrome and De Quervain's Tenosynovitis (Eapen et al., 2014).

For this project the same hand model was used throughout. Naturally these joints have some play on every axis but while texting these levels of play are negligible. In figure 3, F0 denotes the thumb while F1-F4 are the fingers. Figure 3 is a palmar view of a right hand. The axis at the joints have been labelled to show how many degrees of freedom each joint possesses, the wrist has three, CMC and MCP have two, and IP has one.

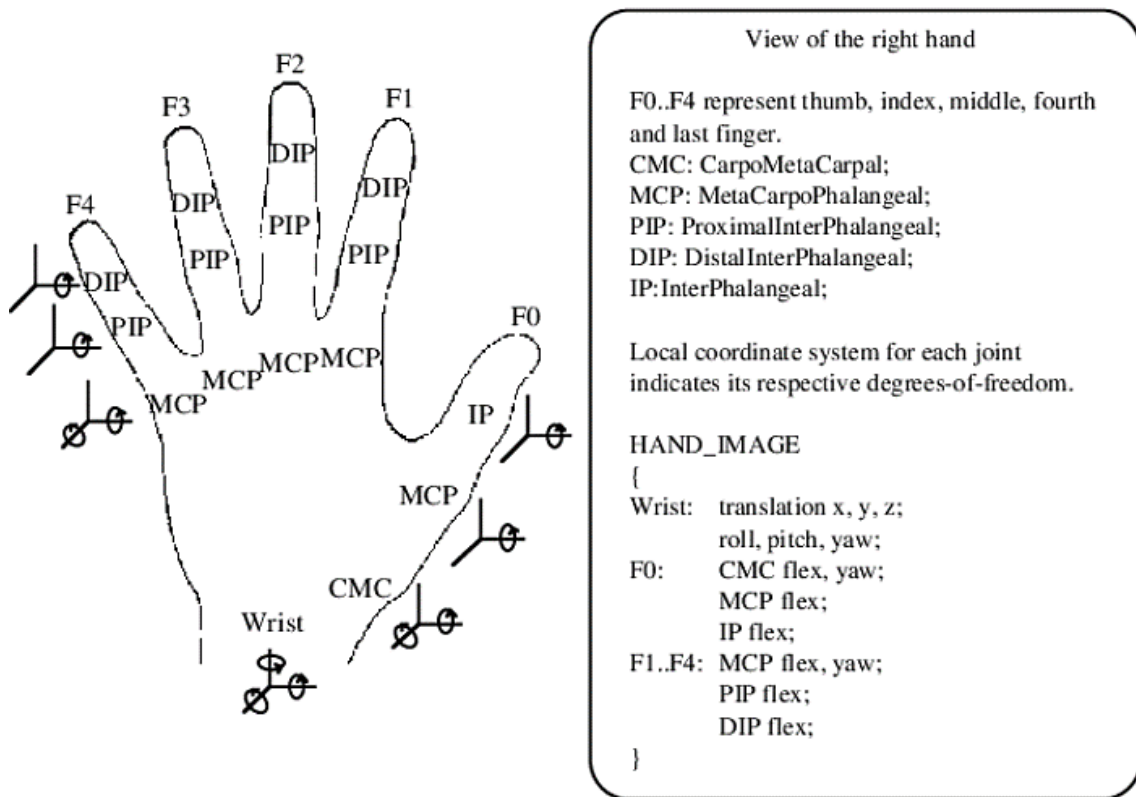


Figure 3: Degrees of Freedom for Hand Joints Model (Roy, 1999)

## 2.2 Repetitive Strain Injuries

Actively repeating a motion causes wear and fatigue on muscle-tendons as the name RSI implies. Abnormal posture also poses a risk of musculoskeletal disorders (Mathiassen, 2006). The following section will describe RSIs expected to arise from one-handed texting.

De Quervain's Tenosynovitis and Extensor Pollicis Longus (EPL) tenosynovitis are debilitating repetitive strain injuries that occur from the overuse of the FPL and EPL muscle-tendons and could be induced by frequent texting (Eapen et al., 2014). These two tendons are attached to the thumb and run down through the tendon sheath (see Figure 4) and into the forearm where the connected muscles are located. Friction

between these tendons and their tendon sheaths may cause inflammation on the radial side of the wrist. Symptoms of these conditions are inflammation at the bottom of the wrist, sharp pain at thumb base, difficulty pinching objects, and thumb movement impairment. The Finkelstein test is one method used to determine if these RSIs may be present. The test is done by tucking the thumb down between all fingers and gently tilting the wrist forward. If tingling, pain, or numbness are present an RSI could be as well.

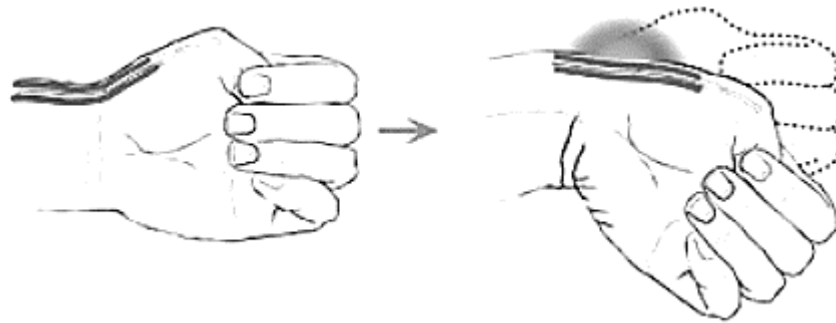


Figure 4: Finklestein Test for De Quervain's Tenosynovitis (DoctorsGates, 2011)

Carpal tunnel syndrome is another RSI to consider. Flexor tendons passing through the carpal tunnel will become inflamed under repetitive strain and take up necessary space for wrist function. This constricts and pinches the median nerve causing discomfort. Numbness and sharp pain in the wrist are the most common symptoms. The test most used by physicians to help determine the presence of carpal tunnel syndrome is the Phalen Test (Almasi-Doghaee et al., 2016). The Phalen test is where elbows are placed on a table, back of hands together and fingers mirrored, and then arms rotating towards the chest allowing the elbows to rise off the table (see Figure 5).

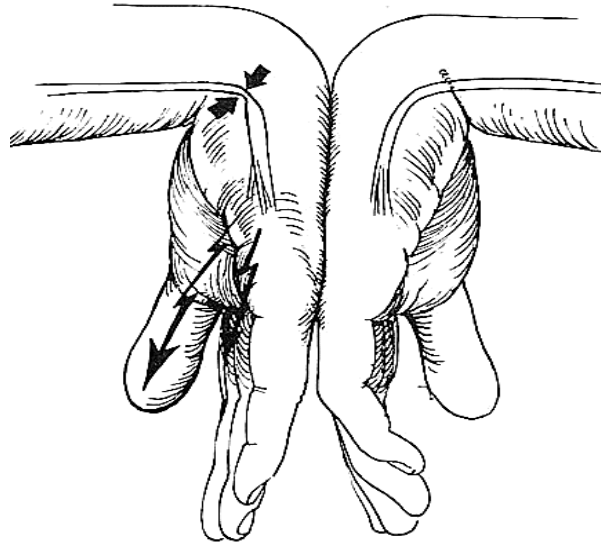


Figure 5: Phalen Test for Carpal Tunnel Syndrome (FreeDPT, 2016)

People with upper-limb loss complete this test with aid. Phalen and Finkelstein tests are more reliable when severe cases are present. Clinicians may administer these tests differently and may lead to contradictions in accuracy (Cunha et al., 2020; Som et al., 2021).

While working at a computer, wrists should not be extended more than 15 to 30 degrees (Rempel et al., 2008). This suggestion should apply when texting as well. While texting, the further from neutral postural joint angles are, the more a person may be at risk of developing a wrist injury.

Chronic pain associated with upper-limb loss is problematic for many people, 90% of respondents to a survey by Hanley reported pain and 76% of those reported more than one kind of pain (Hanley et al., 2009). A repetitive task like texting may lead to unilateral upper limb amputees experiencing more pain than the normally limbed population.

## 2.3 Basic Texting Mechanics

To categorize texting forces appropriately it must be determined what constitutes a large or small force. A study conducted by Amadio where the FPL tendon was put under repetitive strain and friction gliding determined safe ranges of forces. Ranges from 5 to 10 Newtons (see Figure 6) are a safe zone where synergistic rehabilitation takes place, and below 5 Newtons is intended for early stages of rehabilitation that only use passive motion on the FPL tendon (Amadio, 2005). Any forces above 10 N are considered a high force. These guidelines of what are considered high (damaging) forces and lower (healing) forces will be used as benchmarks when analyzing participants forces at different Force Sensor locations.

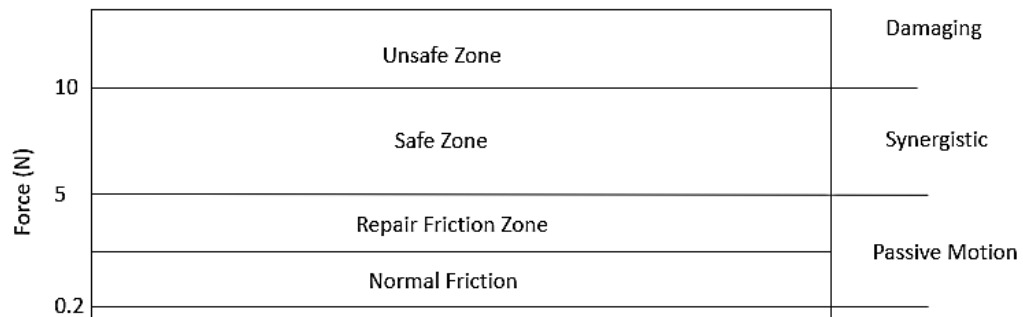


Figure 6: Safe and Damaging Zone for Thumb Tendon Forces (Amadio, 2005)

Figure 7 shows a mobile phone and the rotational movements it may have. Only one study has been identified which measured the stability of mobile phones during a texting experiment, Bernier (2018). This was done by calculating angles of rotation of the phone plane about its X, Y, and Z axes (see Figure 7 for roll, pitch, and yaw). One observation of note that was reported in Bernier's study is that female texters had more

roll than male texters, meaning the phone tilted more front to back. Participants with limb loss showed more yaw in the phone's stability, possibly indicating wrist movement during texting.

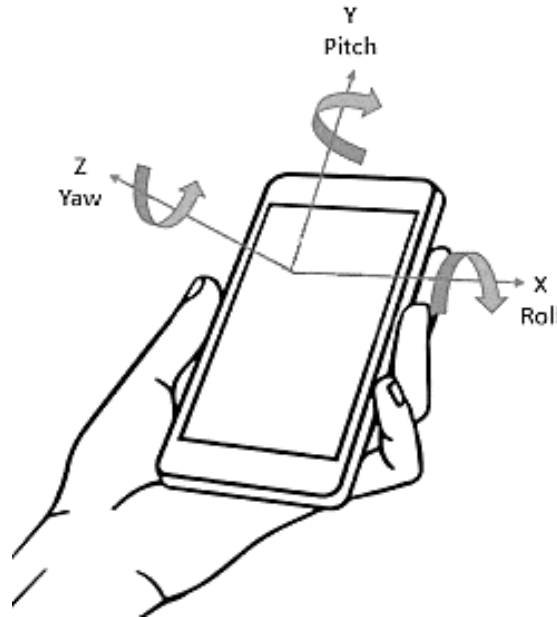


Figure 7: Axes of Rotation on Mobile Phone (Kluva, 2017)

EMG is used in biomedical studies to measure muscle activity. Muscle activity may indicate how often and how much work a muscle is contributing during a monitored task. When working with EMG it is important to know how to filter the signal properly. Sources of electronic noise such as that due to movement artifact, ambient noise in the environment, and 60 Hz line noise, need to be removed from the signal (Chowdhury et al., 2013). Low-pass and high-pass filters will change the raw stochastic signals into ones that can be analyzed. It is important to note that comparing the EMG of one person to another, even with the same instruments and set up, should be used only under ideal circumstances as the signal can change significantly with muscle depth, skin moisture,

and electrode positioning (De Luca et al., 2010). For the current study, EMG will not be analyzed between individuals but will be compared from one mobile device to another.

### **3. Methods**

This thesis has been a continuation of Bernier's work completed in 2018.

Bernier's data collection was thorough and allowed for many variables to be considered in analysis. Bernier's primary goal was to develop investigative methods in one-handed texting analysis. The takeaways that Bernier noted in her own analysis of the data were that increased thumb speed may decrease phone stability, smaller hands (particularly in females) increased concern for negative musculoskeletal symptoms, and that males texted faster than females.

#### **3.1 Survey Information**

The data reported in this thesis were collected in four categories, electromyography (EMG), motion capture, thumb forces, and a survey (including texting habits, pain scales, and anthropometrics). The experiment monitored 23 participants with instrumentation as they completed texting patterns to determine if unilateral upper limb amputees were at higher risk of developing RSIs. A list of the participants details is in the following table (see Table 1).

Table 1: Participant Details

		Normally Limbed	Limb Loss
Sex	Female	n = 7	n = 4
	Male	n = 9	n = 3
Age Range		18 – 53	17 - 41
Mean Age		24.9 +- 5.3	36.4 +- 11.3
Dominance or Remaining Limb	Right	14	2
	Left	2	5
Participants Involved in both Force and EMG		16	7
Participants Involved in Motion Capture		16	6*

\* Note one Limb Loss participant had no motion capture data

Before completing a series of texting trials for the experiment, 23 participants were asked to complete a survey with three categories. The survey included several sections: general information, pain, and various other measurements such as hand size and grip force. The survey used can be found in Appendix B.

The first section contained questions regarding sex, age, height, and weight. This was followed up by information about their texting habits including how often they text and how often they text one-handed. Some additional information was asked about computer use and other activities where arms and hands are completing repetitive tasks (i.e. sports, computer gaming, needle craft). This information was used to search for patterns between texting (or other activities), pain, and measurements from the experiment.

Referring to Table 2, the left side compares information from the survey of the limb loss and control group (Limb Loss = 7, Control = 16) regarding how many text

messages they send, how often they text one-handed (0-4 scale or 25% increments), average weekly physical activities (in hours), and daily computer use (in hours). The same comparisons are made on the right side grouped by sex (M = 13, F = 10). Groups were defined based on their texting habits and tasks that use repetitive hand motion, for example, light texters and heavy texters. Heavy texters can be defined as those who send more than 100 text messages per day. Males in this study texted an average of 22 more times per day than females but a t-test showed no significant difference due to widely varying ranges (P = 0.22). The control group on average texted 53% of the time one-handed and females within that group texted one-handed 14% more often than males. No significant difference was found when comparing weekly computer time and activities based on limb status or sex.

Table 2: Texting Habits Limb Loss and Sex Comparisons (made in Minitab) (Limb Loss Comparison Left, Sex Comparison Right)

<b>Variables</b>	<b>Limb Loss</b>	<b>Mean</b>		<b>Sex</b>	<b>Mean</b>
Texting (Texts/day)	No	93.4		F	76.5
	Yes	79.3		M	98.8
One-Handed (0-4)	No	2.13		F	3.00
	Yes	4.00		M	2.46
Activities (Hours/week)	No	6.00		F	4.00
	Yes	4.71		M	6.85
Computer (Hours/day)	No	3.81		F	3.30
	Yes	3.00		M	3.77

The second section asked for details of pain in localized body parts. Pain in the thumb, wrist, forearm, elbow, shoulder, neck, and back were all analyzed. The participants were asked to report pain on a scale of 0-10 referring to a pain scale provided (see Figure 8). This information was analyzed with other experimental measurements such as forces, EMG, and posture to find the links between other variables and pain.

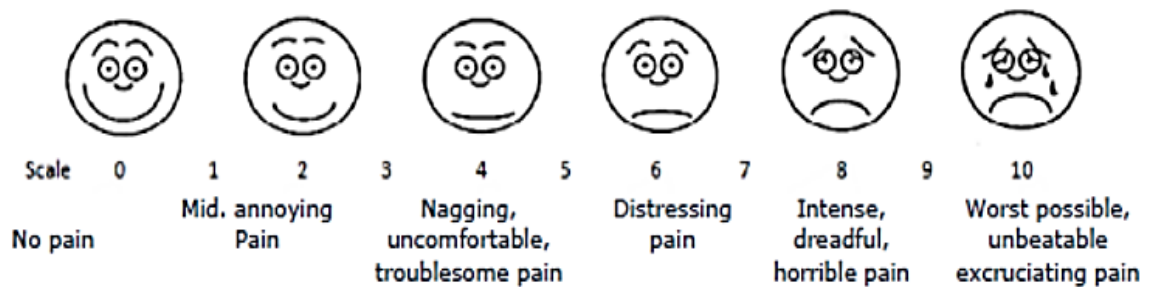


Figure 8: Pain Scale 0-10 (Duly Disabled, 2017)

The limb loss group reported higher pain in every category except neck pain (see Figure 9). There was much higher wrist pain reported by the Limb Loss group ( $P < 0.05$ ) (see Figure 10). There is no significant difference in wrist pain reported between sexes, however females scored slightly higher in pain reporting overall (Figure 11) ( $P = 0.462$ ). Figure 9 is including in this section for the purpose of showing pain clearly differed in the Limb Loss and Control group.

### Pain Overview of Limb Status

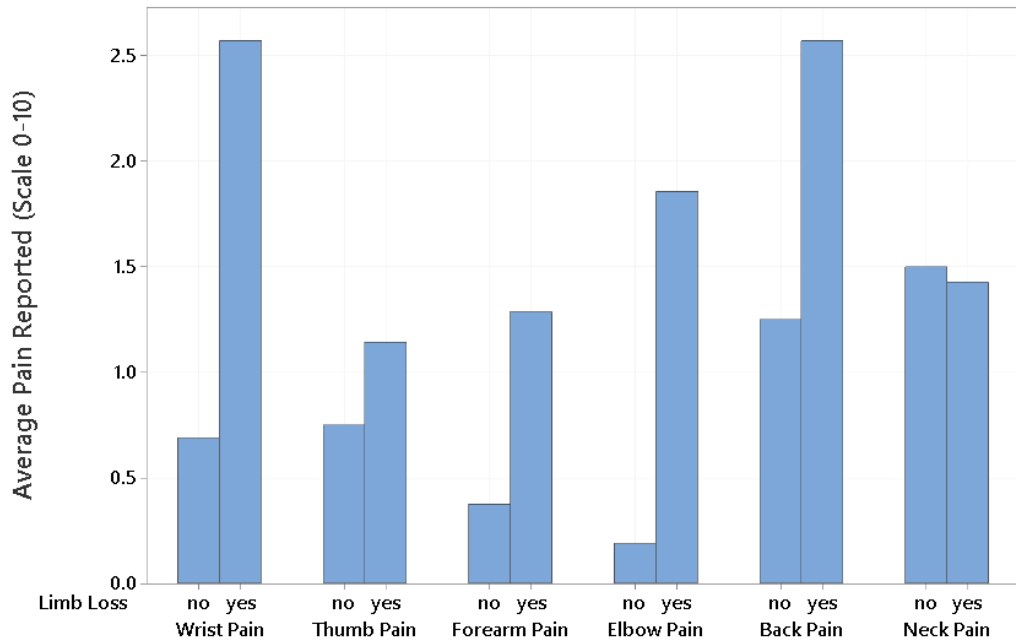


Figure 9: Pain Reported by Control Group (left bars) and Limb Loss (right bars)

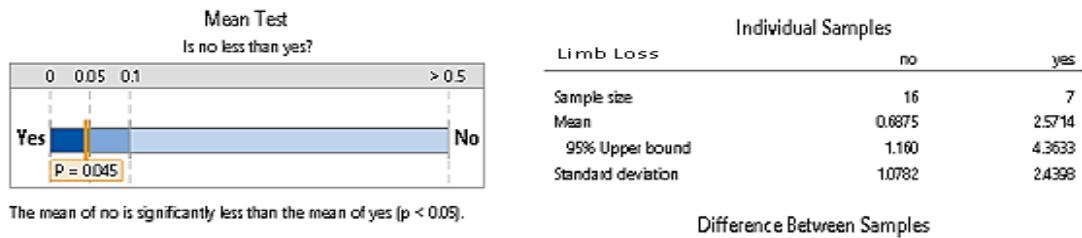


Figure 10: 2-sample T-test of Wrist Pain Limb Loss vs Control

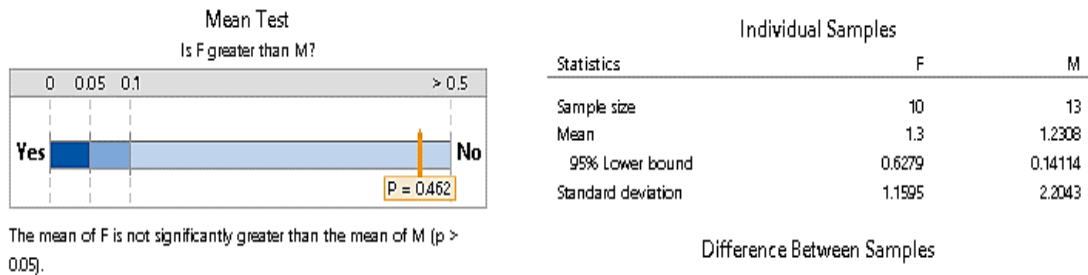


Figure 11: 2-sample T-test of Wrist Pain of Sexes

When the participants were asked to complete Phalen, Finkelstein, and grip strength tests they also reported on any pain during those tests. Descriptions of the pain experienced were tingling, numbness, or pain, as can be seen in figure 12. As stated previously, these two tests do not necessarily indicate an RSI and should only be used as a possible indicator. It is very unlikely 16 to 18 of the participants in this experiment (n=23) have de Quervain's Tenosynovitis or Carpal Tunnel (see Figure 12) as they only affect two to three percent and three to six percent of the general population respectively (LeBlanc & Cestia, 2011; Pike, 2018).

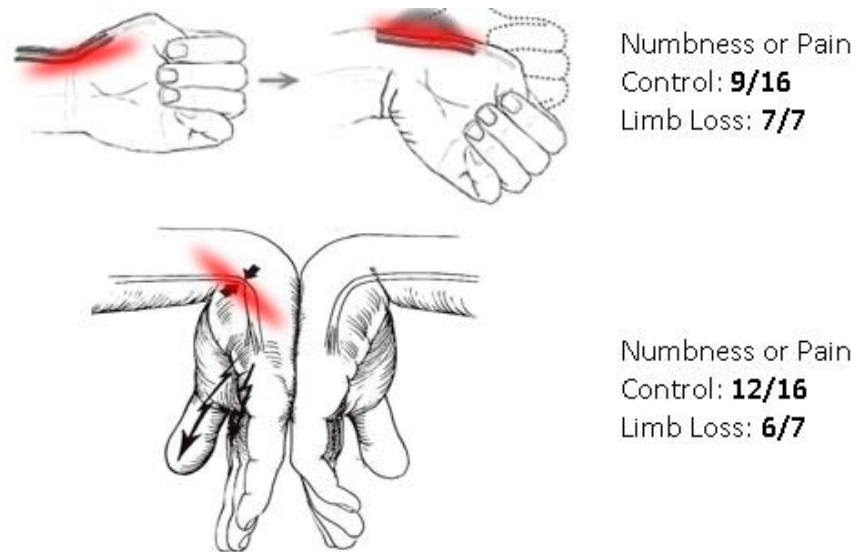


Figure 12: RSI Testing Pain Reporting (DoctorsGates, 2011; FreeDPT, 2016)

From the participant's surveys, hand anthropometrics and the thumb's range of motion were recorded. Anthropometrics of the hand were measured at various points (see Figure 13). With this information the relationship between forces, EMG, phone size, and kinematics to hand size were analyzed. The thumb's range of motion at various angles was measured using an angle marked box (see Figure 13). This is useful information for analyzing texting mechanics to see relationships between thumb

flexibility and factors such as pain, stability, and forces as the thumb is required to reach extreme positions on the phone's keypad.

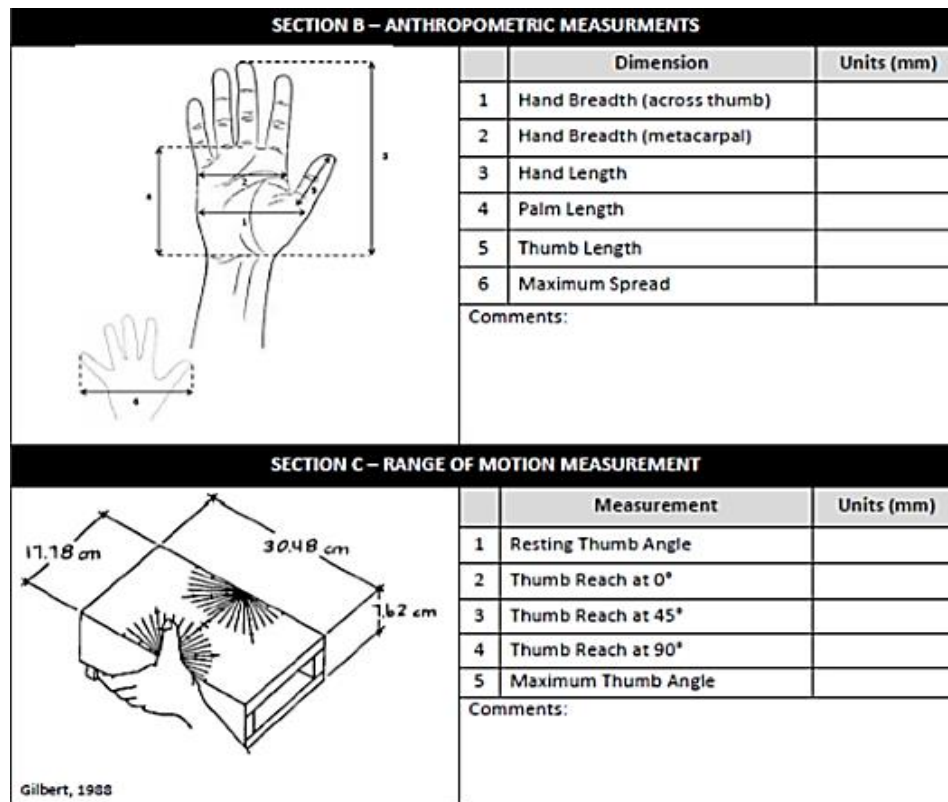


Figure 13: Measurements for Hand Size and Thumb Range of Motion (Gilbert, 1988)

These measurements were used to find if there were advantages to having larger or smaller hands when using mobile phones or if higher range of motion of the thumb (can be thought of as thumb flexibility) had any effect on texting mechanics, especially on the far side force sensors away from the thumb base. Some things that hand size and thumb range of motion would factor into are their effect on thumb forces, the angles of thumb contact, stability of the phones, texting efficiency, and pain metrics.

### 3.2 Motion Capture

Part of this research involved analyzing the postural angles of amputees compared to non-amputees while texting. Postural angles were calculated to find the angle between two vectors created by using sets of points from the 27 reflective markers that were located on the hand, arm, back, neck, and head (see Figure 14).

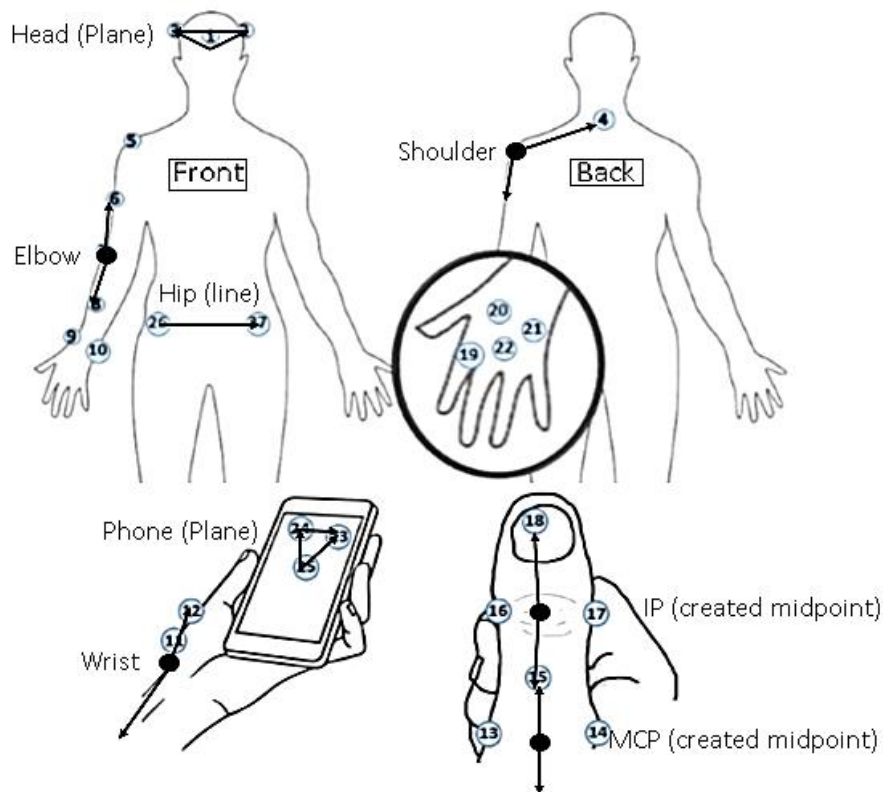


Figure 14: Marker Placement for Motion Capture (Bernier, 2018)

Some positional calculations such as IP, MCP, and wrist angles were calculated relative to the phone's axes while others like elbow, shoulder, neck, and back were relative to the global coordinates of the VICON system's capture volume. Some midpoints were created by averaging two other points (see Figure 14 above and take the midpoint of the IP for example).

To calculate joint angles an equation was derived by the dot product between vectors ‘p’ and ‘q’. The vectors ‘p’ and ‘q’ were obtained in MATLAB by subtracting the three points that that make up the angle by the midpoint, making the new midpoint [0 0 0]. The result is having vector origins that can be calculated using the following equation (see Equation 1).

Equation 1: Angle Between Vectors Equation

$$\cos\theta = \frac{\mathbf{p} \cdot \mathbf{q}}{|\mathbf{p}| \cdot |\mathbf{q}|} = \frac{p_x q_x + p_y q_y + p_z q_z}{\sqrt{p_x^2 + p_y^2 + p_z^2} \sqrt{q_x^2 + q_y^2 + q_z^2}}$$

The motion data were collected at 60 Hz while force and EMG were at 1000 Hz. Motion data have been upsampled and interpolated to 1000 Hz using “upsample” functions in MATLAB and are the same array length as their corresponding force and EMG data for each experiment trial. Upsampling was used instead of downsampling (decimating) as the force and EMG both have high frequency components and would not pass Nyquist criterion otherwise (Broesch, 2009). The Nyquist theorem is a mathematical principle that states the signal's highest frequency rate must not be more than half the sampling rate used to acquire that signal.

### 3.3 Forces

The phone screen keyboard was mimicked using specifically placed force sensors. Five force sensors were used to measure the normal forces applied to them, four in the corners and one central. Participants when doing texting trials completed the same pattern marked by the arrows in Figure 15 below. Control group participants also completed two-handed (two-hands supporting, one thumb texting) texting to compare

the mechanical differences between two-handed and one-handed texting. Throughout this report force sensors are referred to as A through E in the order they appear in the pattern and in some instances 1 through 5 in figures. The force sensors were calibrated for each participant, collected at a sampling frequency of 1000 Hz, and had a maximum reading of 15 N. Several participants slightly surpassed the maximum force threshold.

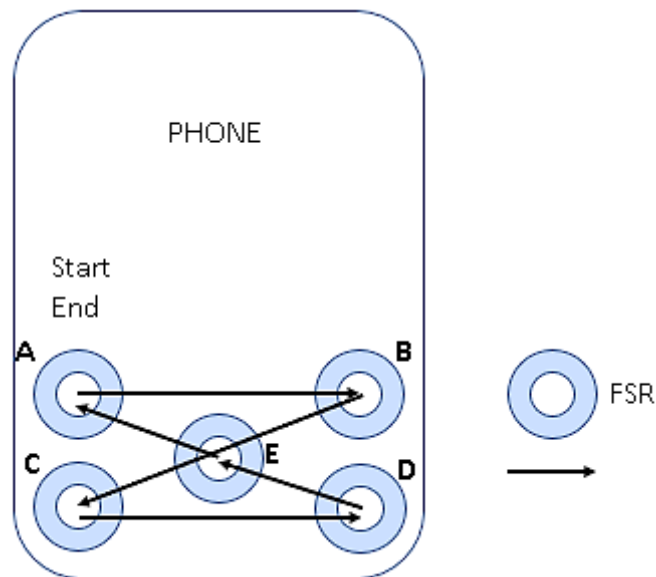


Figure 15: Pattern Directions of Texting Trials

Repeated patterns are useful to compare thumb position, velocity, acceleration, repeatability of kinematics, and most importantly to allow consistency in conditions for averaging. Timing information can also be gathered by measuring the thumb movement time required between force and EMG peaks (force peak to peak time denoted by arrows in Figure 16), and keystroke durations were measured at 30% of the force curve peak to keep participant to participant comparisons standardized.

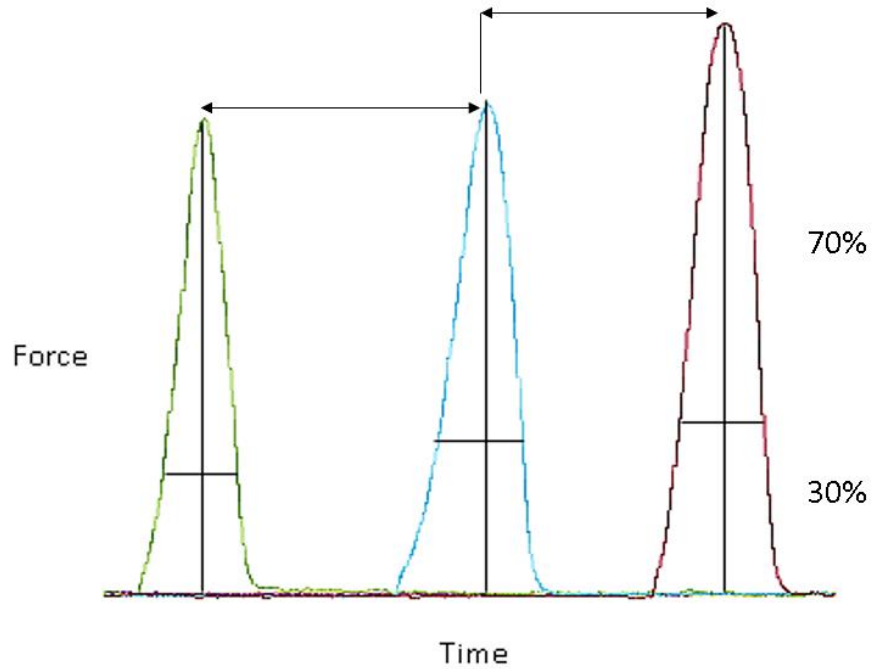


Figure 16: Force Peaks and Duration Measurements

While texting one handed there will naturally be areas of the phone's keypad that are harder to reach with the thumb than others. The five force sensors have been mapped for easy referencing seen in Figure 17. For example, the force sensor in the top left corner of the figure is top-far side. Always assume a right-handed orientation in this document unless specified otherwise. This will be useful to compare force location data.

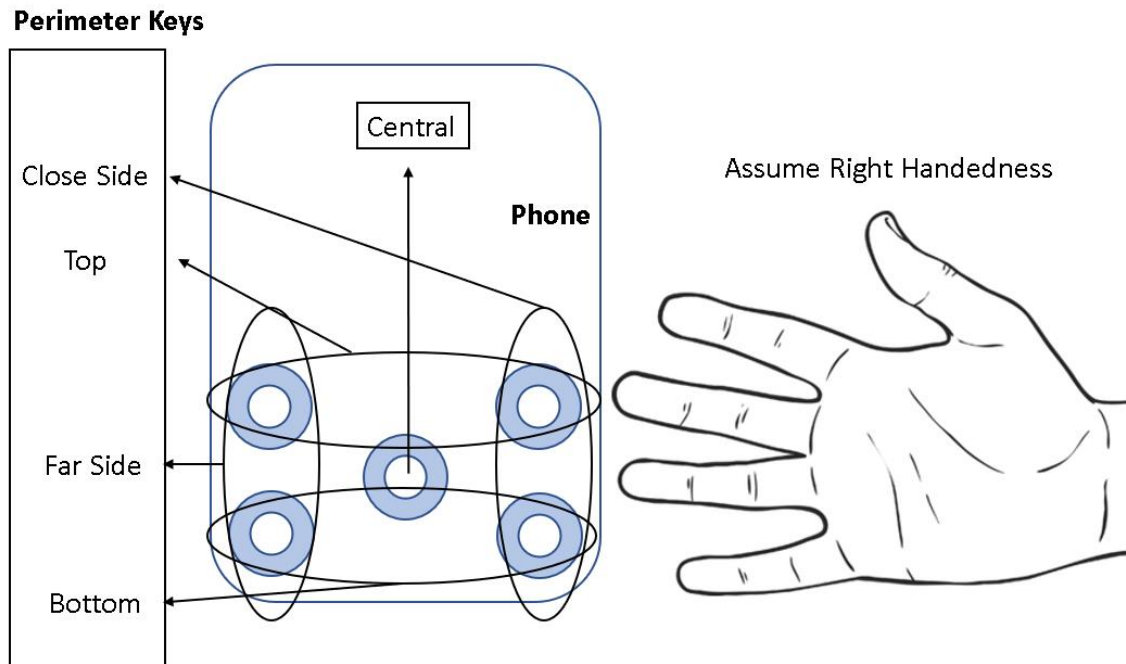


Figure 17: Force Sensor Location Guide

### 3.4 EMG

Unfiltered EMG data is difficult to interpret as it can be tougher to see the true pattern, amplitude and durations. Smoothing the data and using absolute values is better visually for graphing as well as calculations and analysis. “Corrected” EMG was applied the same way to all participants and their trials.

A concentric electrode was attached to the Abductor Pollicis Brevis to monitor muscle activation when the thumb abducted during the experiment pattern. EMG data were collected at a DC offset of roughly 2.5 mV and stochastic, and therefore needed to be processed. By subtracting the offset (or the true average of that trial as it varied slightly with each) from all EMG data points, the average becomes 0 and thus eliminates the offset. Notch filtering was used to remove powerline noise. The data were then smoothed using a Gaussian window filter, the absolute positive of their arrays were then

taken. A zero-phase noise filter was used to remove any other noise (the `filtfilt` function in MATLAB). Zero-phase filters are a forward-backward filter with a phase slope of zero and a real even number impulse response (MATLAB, 2021). Figure 18 shows an example of the before and after of the EMG signal.

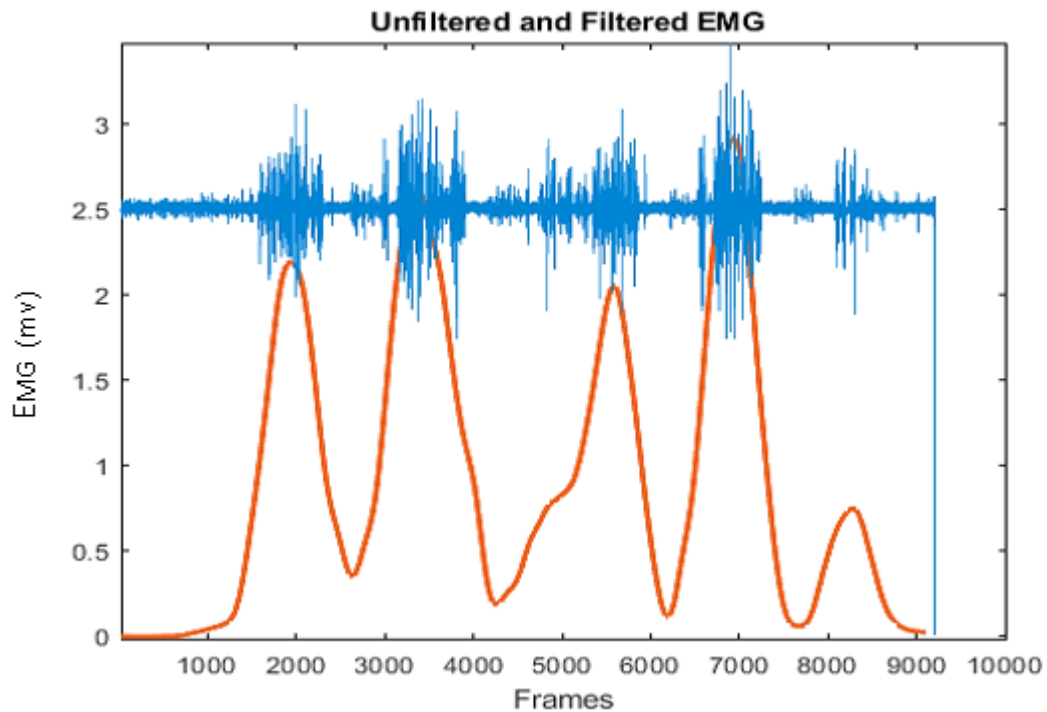


Figure 18: Example of Unfiltered and Filtered EMG Signal

EMG peaks were expected to be higher on larger phones as they were more difficult to handle for certain participants and it was reported that they required more effort to reach keys on the far side of the phone. Results can be found in section 4.2.2 of this report "EMG and Phone Size".

### 3.5 Data Acquisition Method

Three different smartphones were used by participants, the iPhone 4, Samsung Galaxy 3, and the Samsung Galaxy Note. The Note proved to be too large for six

participants (four Control and two with Limb Loss) to use so some trials were incomplete. Table 3 details the types of phones used and dimensions that are referenced throughout the report. The Note phone was significantly longer, wider and heavier than the Samsung Galaxy 3, and the smallest was the iPhone 4.

Table 3: Phone Sizes

Phone	Length (mm)	Width (mm)	Weight (g)
iPhone 4	115	59	140
Samsung Galaxy 3	137	71	133
Note	147	83	178

The trials of each participant were ordered as seen in Figure 19 below. The order of the phones used were randomized. Pattern and number of hands used were always short before long and one-handed (OH) before two-handed (TH).

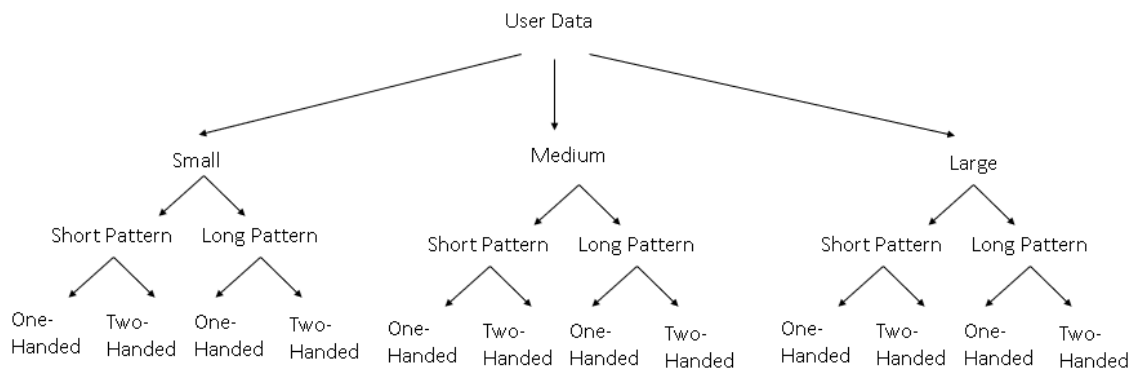


Figure 19: Breakdown of Texting Trials Completed by Participants

The data folders from the previous study had consistent naming errors from the standard format, so a script was written to find the inconsistencies and correct them. All excess file types were also removed in this step that came from the VICON configuration, filtering variables, and any extra files created by the GUI. Once naming

variables were corrected another script was made to gather all the data that were in separate folders and then saved them all in a structure by using a loop to search and find each individual trial of all participants and save them in a conventional manner. Table 4 shows the depth of each structure. Force and EMG were collected and saved to the same arrays during each trial and are found in the fifth layer of the structure under F\_EMG; this layer also contains all the motion capture markers.

Table 4: Post Processed Data Structure

Participant	Phone	Pattern	Trial	Marker EMG	X Y Z (Coordinates)
1	iPhone		T01	FRHD	. . .
.		Short Pattern	.	.	. . .
.	Samsung		.	.	. . .
.			.	C7	<b>1 2 3 4 5 6 (Channels)</b>
23	Note	Long Pattern	T28	F_EMG	. . . . .
					. . . . .

### 3.6 Hypothesis Testing

Several graphical tools and analysis of variance statistics are used throughout this thesis. Here is a brief description of these methods.

Boxplots are a plotting tool that show the distribution of data where an interquartile range of 25% to 75% are inside the box and the remaining ranges are on the whiskers (see Figures 20). If there is no whisker then a quartile of data resides at the box's maximum or minimum. A mean or median point is often found inside the box.

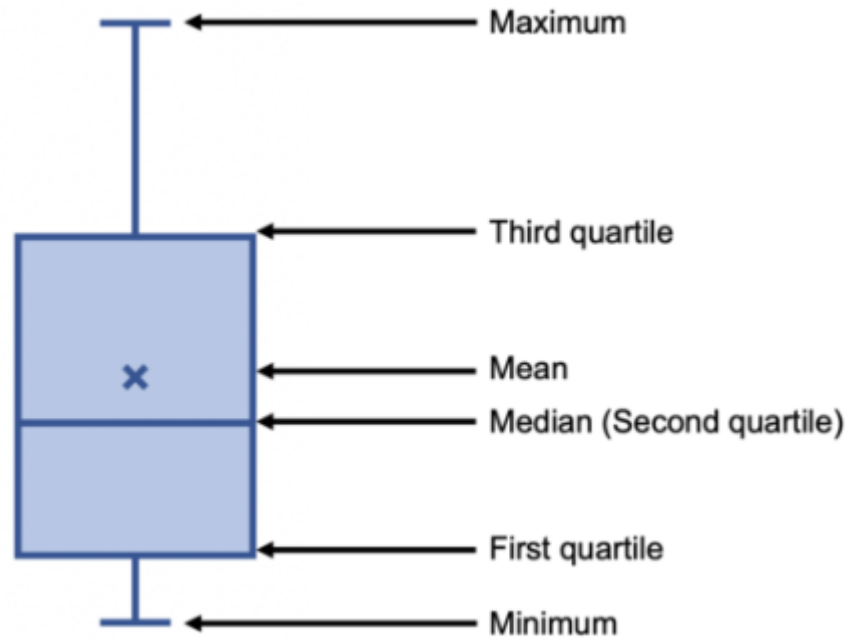


Figure 20: How to Read Boxplots (Bounthavong, 2019)

Regression lines were used in scatterplots to show the line of best fit for data that compares two independent variables. The lines of best fit and percentage outcome were found using Minitab software. To put it in its simplest terms the means and standard deviations of the X and Y values are used to calculate the slope and intercept for the line of best fit and the percentage indicates how much of the data can be explained by the line (or the variance). A positive slope indicates a positive relationship between variables while a negative slope shows a negative relationship. See figure 21 below for an example of variables with a negative relationship (Patterns were completed faster with Wider Hands). However, the  $R^2$  value is low at only 25% so evidence of a relationship between the variables in this example is marginal. As the population size of this study was 23 participants  $R^2$  values above 40% are considered a strong relationship.

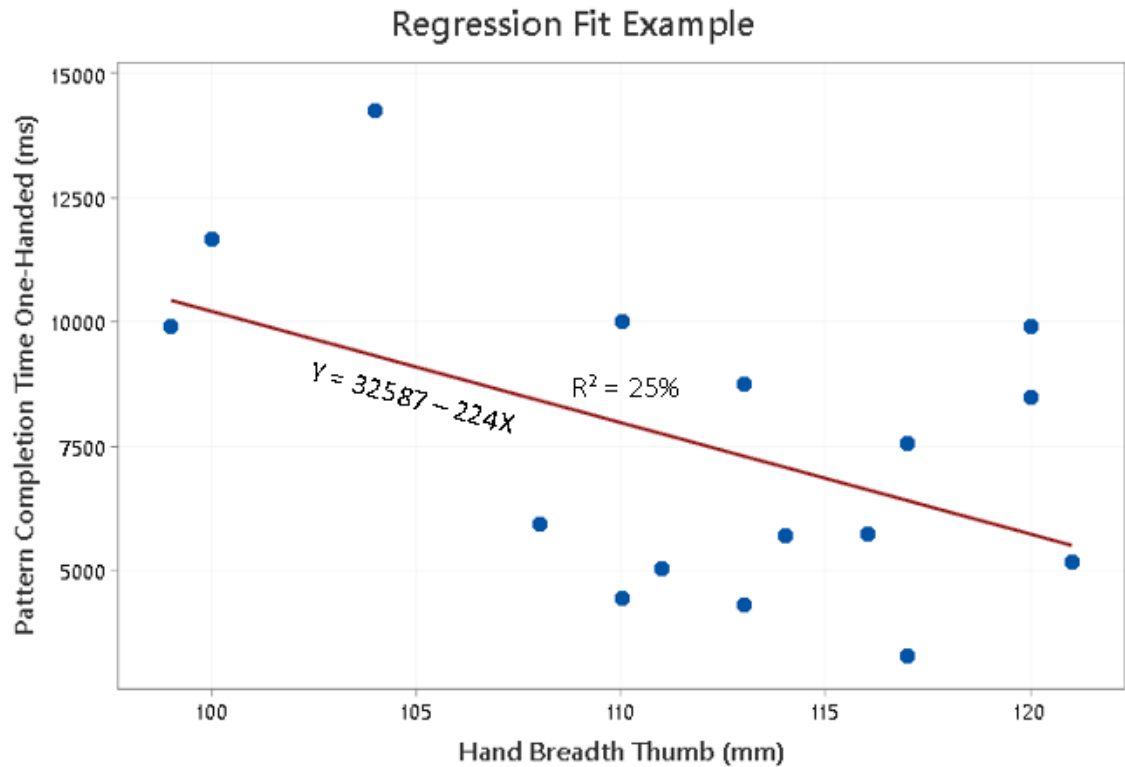


Figure 21: Example of a Regression Fit (Made in Minitab)

T-tests are statistical tests of a hypothesis that are based on the distribution of data to determine if they are significantly different or the same. This thesis uses both 2-sample t-tests and paired t-tests. 2-sample t-tests were used to compare independent groups of data for a variable; for example comparing the forces experienced by a single force sensor between the Limb Loss and Control group. Paired t-tests were used to compare dependent variables such as the difference between force experienced on one force sensor and another. The significance level for a null hypothesis in this thesis was  $\alpha = 0.05$ .

## **4. Results and Analysis**

Participants were only asked to repeat patterns with 10 to 20 keypresses in a trial. There was no literature found regarding how many words are in a typical text message, but we will assume it is roughly 10. If the average length of an English word is 4.7 characters (Garbe, 2018) and the CWTA reported the average Canadian sends 50 texts and 27 e-mails per day on a mobile phone, this means people are pressing their mobile keypads about 3600 times per day. Therefore, when we consider things such as pattern completion time, thumb movements, forces, and muscle activation it is important to have this context. The reduction of risk for RSIs is the ultimate goal of this research so the implication that these aforementioned variables are compounded over the length of a person's day must be noted. For example, if participant A and B both text 50 times per day however participant A takes 5 seconds longer to complete every text, they will be subjecting their musculoskeletal system to an additional 4 minutes of texting-related exertion per day.

### **4.1 Pain and Joint Angles**

#### **4.1.1 General Pain**

Pain in the Limb Loss group was higher than the Control group as was seen in literature. Even with a small population it was determined that pain reported by the Limb Loss group in the wrist, forearm, and elbow were significantly higher ( $P < 0.05$ ) (see Figure 22). The thumb had no significant difference in pain. The Phalen and Finkelstein tests were not reported on a scale of 0-10 (e.g. thumb pain, wrist pain, etc.) but rather by no pain, tingling, numbness, and pain.

For hypothesis testing purposes these 4 categories were ranked 0 to 3 (i.e. no pain = 0, tingling = 1, numbness = 2, pain = 3). Limb Loss was significantly more sensitive to the Finkelstein test than the control ( $P < 0.05$ ) with 6/7 reporting at least tingling sensations, and 8/16 from the control group. The Phalen test also had more impact on the Limb Loss group where 7/7 reported pain and 7/16 reported pain for the control group. The Phalen test had the Limb Loss group report an average 2.714 out of a possible 3 on the arbitrary pain scale for this test. With this information it appears that the Limb Loss group has pre-existing hand, wrist, and forearm pain potentially making them a higher risk for the RSIs being examined. A larger population study would be necessary to solidify this claim though as the standard deviation was often higher than the mean, indicating a high coefficient of variation.

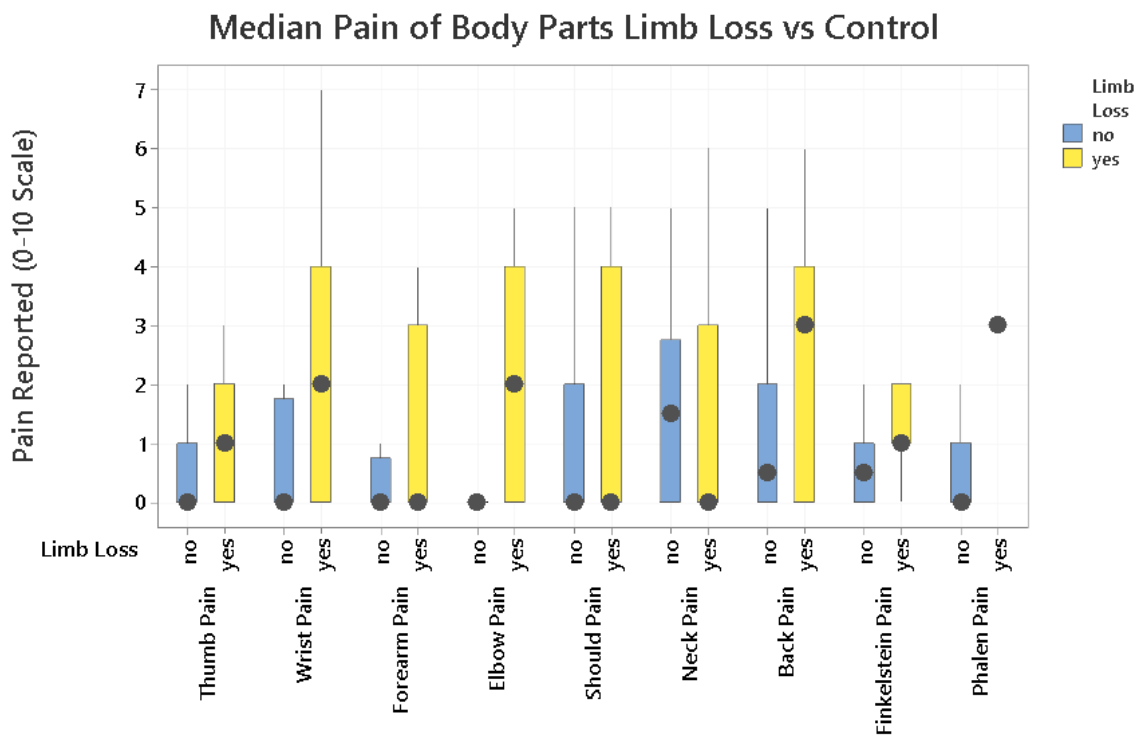


Figure 22: Median Pain Reported by Participants (Limb Loss vs Control Group)

There was a high degree of correlation for the different types of pain participants reported in their surveys (e.g. thumb pain and forearm pain), as well as pain reported in relation to postural angles of the thumb, wrist, and elbow (see Table 5). This means someone who reported one type of pain was likely to also report another while those who reported no pain rarely reported pain in other areas either. Correlation measures the strength of a relationship between two variables. Pearson's correlation (used for this study) is calculated by the covariance of the two variables and then divided by the multiplication of both variable's standard deviation (see Equation 2). Some correlations drawn such as Elbow Pain and IP angle are not ergonomically related, however it is consistent in this population that having one body area with pain increases the likeliness of pain in another body part. More areas with pain may increase the risk of RSI presence.

Equation 2: Covariance and Correlation Formulae (Zaiontz, 2020)

$$cov(x, y) = \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}) / (n - 1)$$

$$r = cov(x, y) / s_x s_y$$

Table 5 : Correlation for Kinds of Pain and Wrist Angle

<b>Pain and Posture</b>	<b>Correlation (-1 1)</b>	<b>P - value</b>
Finklestein Pain – Wrist Angle	0.640	0.001
Phalen Pain – Wrist Angle	0.766	0.000
Thumb Pain – Wrist Pain	0.494	0.016
Forearm Pain – Wrist Pain	0.465	0.025
Elbow Pain – Wrist Pain	0.707	0.000
Phalen Pain – Wrist Pain	0.536	0.008
Forearm Pain – Thumb Pain	0.535	0.009
Phalen Pain – Finklestein Pain	0.646	0.01
Wrist Pain – Wrist Angle*	0.447	0.121 (0.033)*

\* *Interestingly Wrist Pain and Wrist Angle correlation was not as strong as other pain and posture relationships. After applying a Bonferroni correction, the significance changes to  $P < 0.05$ . Removing one outlier from the equation also makes the correlation significant with a  $P$  value  $< 0.05$ .*

Wrist pain was the highest reported area of pain below the shoulder from the survey overall; 80% of participants who reported wrist pain also had thumb pain, 60% had forearm pain, and 50% had elbow pain as well.

Above the shoulder there was pain reported in both groups, but no significant differences were found in the shoulder, neck, and back based on Limb Status or Sex. However, when groups were separated by age into groups above and below 30, the above 30 age group reported significantly higher wrist pain ( $P < 0.05$ ).

Participants were asked to report any pain experienced while the Phalen and Finklestein tests were administered. They were asked during these RSI screening tests if they felt either tightness, tingling, numbness, or pain. Ten of the 23 Finklestein tests and seven of the 23 Phalen tests were reported as painful. It must be reiterated that these tests only reveal the possibility of an RSI or RSI developing. Four out of 10 instances of pain

for the Finkelstein pain tests were reported by the Limb Loss group and five of seven for the Phalen. This corresponds with previously mentioned t-tests where higher wrist pain was experienced by the Limb Loss group ( $P < 0.05$ ). The pain statistics from the Finklestein and Phalen tests will be considered in the consolidated risk report later in this document (section 4.5).

#### 4.1.2 Joint Angles and Range of Motion

A 2-sample t-test revealed that neither sex nor loss of limb status differed in means for range of motion in this population ( $P = 0.640$ ,  $P = 0.653$ ). Standard deviation of the Female group showed three times the deviation from the mean. The Limb Loss group and Control group had similar reach angles for all thumb reach measurements as well (Maximum Thumb Reach used in Figures 23 and 24 below). When comparing groups by either sex or limb status range of motion was not a factor.

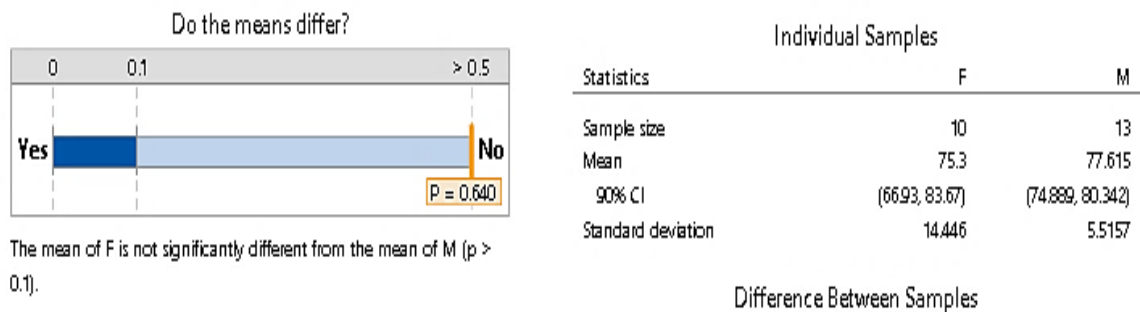


Figure 23: Range of Motion Sex Comparison Showing No Difference in R.O.M (Made in Minitab)

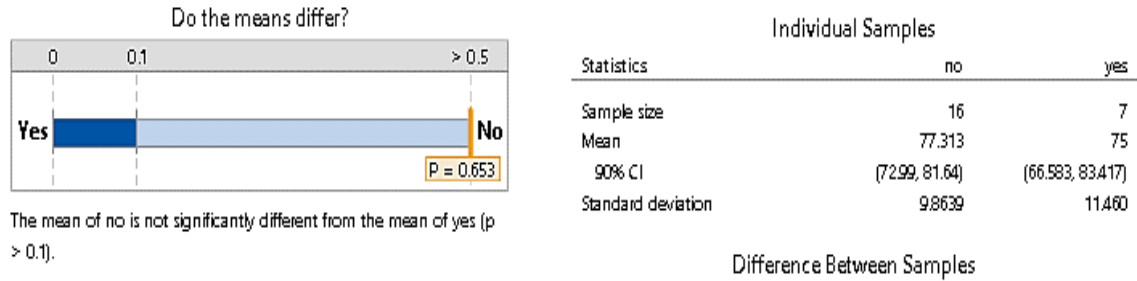


Figure 24: Range of Motion Limb Loss Comparison Showing No Difference in R.O.M  
(Made in Minitab)

Neither IP nor MCP flexion of the thumb changed as phone size increased. Additionally, it has already been established that there was no connection between thumb angle and the resultant force. When looking at the thumb angle as the phone size changed it was expected that the larger phones would require flatter thumbs while reaching to the far side force sensors. However, no significant difference in thumb joint angles were found for participants who were able to hold the largest phone (six participants were unable to properly use the largest phone at all, 4 control and 2 with limb loss).

Analysis of the thumb angles for the IP and MCP joints were compared by both limb loss status and sex (see Figure 25 for IP example). Only force sensors at the bottom-close side, central, and top-far side locations (assume right handedness) were used because the angles at the central force sensor never varied more than a few degrees with the bottom-far side and top-close side sensors. Top-far side and bottom-close force sensors were along the line of thumb motion requiring flexion and extension respectively to be reached. The difference between a thumb in extension and flexion

along this line of thumb motion (or top-left and bottom-right) is approximately 33 degrees.



Figure 25: Visualization of IP Joint Angle (Quigley et al., 2016)

There was no significant difference found between Limb Loss and Control group thumb angles at any force sensor location, the maximum mean difference being only 4 degrees. When the same comparison was made between sex's angles at the top far-side (assume right-handed, Force Sensor A) and bottom-close side (Force Sensor D) of the smallest phone (iPhone) females had flatter thumb angles ( $P < 0.05$ ) (see Figures 26 and 27).

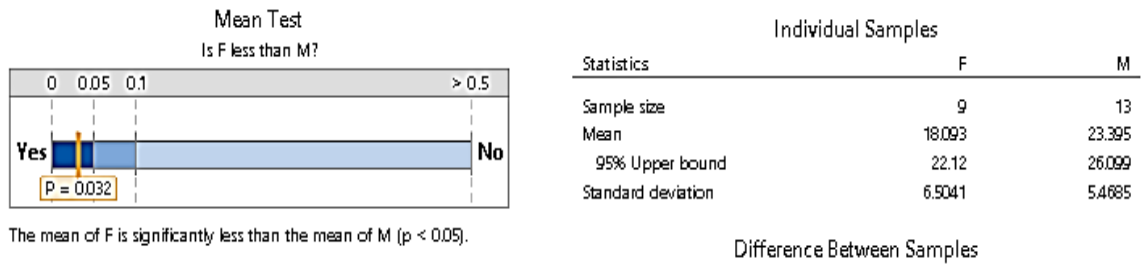


Figure 26: IP Joint Angle Sex Comparison of Small Phone Force Sensor "A" (Made in Minitab)

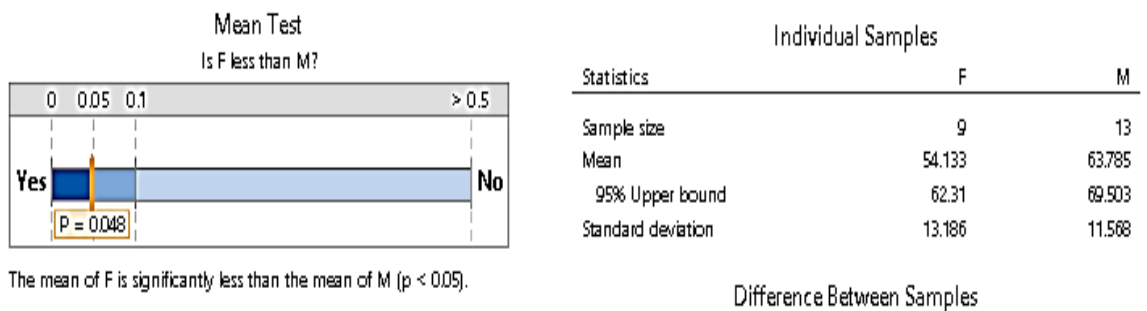


Figure 27: IP Joint Angle Sex Comparison of Small Phone Force Sensor "D"(Made in Minitab)

The angles of the neck, elbow, and hips (relative to the floor plane) were found using linear algebra with point to plane, line to plane, and plane to plane calculations in MATLAB. No significant differences were found comparing Sex or Limb Loss groups. The following table shows the formulas used (see Table 6). The variables of the table  $x$ ,  $y$ ,  $z$ ,  $a$ ,  $b$ , and  $c$  are of individual points, and points that make up lines and planes. Subscript numbers 1 and 2 represent different points of each variable.

Table 6: Formulas Used in Postural Comparisons (Toppr guides, 2018)

Calculation Type	Formula
Distance between 2 points	$\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$
Angle between a Line and Plane	$\sin \theta = \frac{a_1 a_2 + b_1 b_2 + c_1 c_2}{\sqrt{a_1^2 + b_1^2 + c_1^2} \sqrt{a_2^2 + b_2^2 + c_2^2}}$
Angle between 2 Planes	$\cos \theta = \frac{a_1 a_2 + b_1 b_2 + c_1 c_2}{\sqrt{a_1^2 + b_1^2 + c_1^2} \sqrt{a_2^2 + b_2^2 + c_2^2}}$
Distance between a Point and Plane	$D =  ax_1 + by_1 + cz_1 - d  / \sqrt{a^2 + b^2 + c^2}$

When analyzing wrist flexion and extension it was found that the Limb Loss group extended their wrists 14 degrees further than the control group while texting ( $P < 0.05$ ). Recall the wrist was commonly reported to have pain in both groups but more significantly in the Limb Loss group. The pronounced angle while texting on mobile devices could be a risk for RSIs, specifically Carpal Tunnel Syndrome.

The thumb's range of motion data were administered t-tests that revealed no differences in Male vs Female, or Limb Loss vs Control comparisons, meaning each angle of the thumb measured (Resting, 0, 45, 90, and max reach) were similarly distributed in any group comparison.

From section 3.3 "Forces", far side force sensors had smaller overall forces than central and close side force sensors and this was expected to be tied to thumb reaching ability. The Limb Loss and Female groups did not have higher forces due to reaching ability, suggesting the difference was likely related to the population size available for this study.

### 4.1.3 Phone Stability

The stability of the mobile phones in this study was measured using three markers attached to the phone's surface to create an artificial plane (or X and Y axis). Phone rotation about the three axes can be described as pitch, roll and yaw (Bernier, 2018) (see Figure 28).

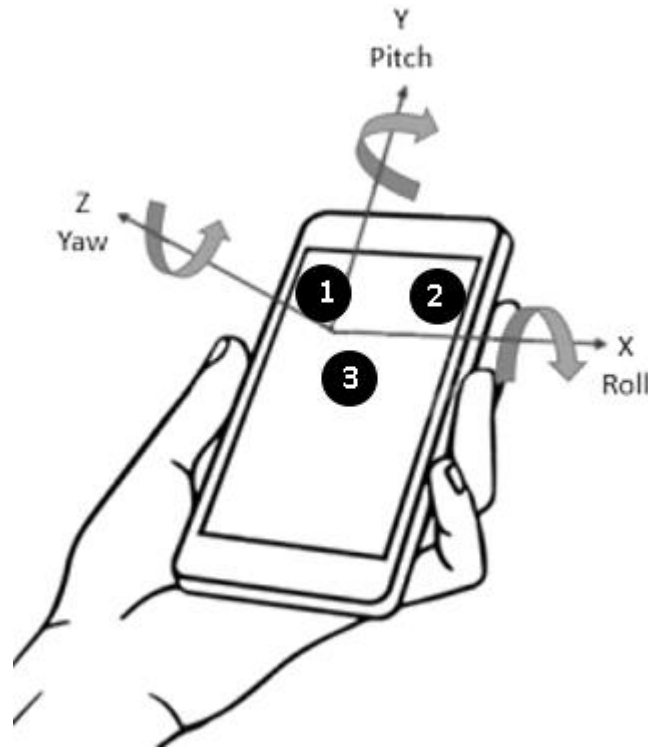


Figure 28: Axes of Rotation for Phone Stability

The phone plane created using the 3 markers was measured relative to the floor plane in Bernier's study and the results are as follows: one-handed texting had more variability in Pitch than two-handed, females had larger variance in Roll, and the Limb Loss group had less variance in Yaw.

In the current study, the three reflective markers on the device's surface were analyzed by variability of translational movement as well. This was done to reveal

whether phone stability had higher variance along the x, y, or z axis, then make group comparisons as well to show which phone type had the most variance (see Figure 29).

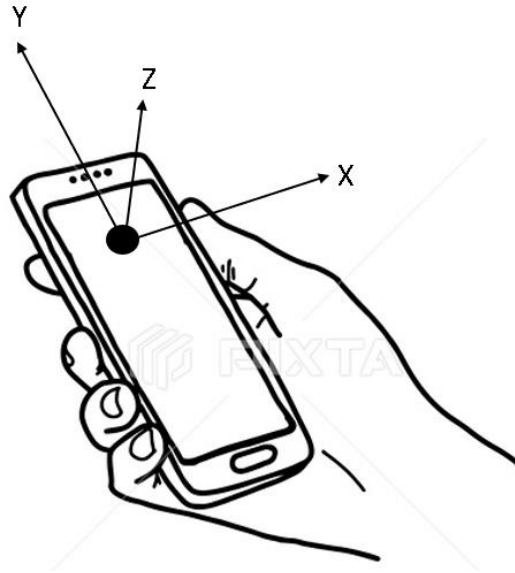


Figure 29: Translation Axes for Phone Stability Using One Marker

Note that these axes are relative to the floor to follow phone movement in free space and not a fixed axis of the phone. The markers are located at the top of the device while a mobile phone is held near the bottom and typically anchored against the meaty part of the thumb (or the adductor pollicis brevis).

Each of the 3 sections of the figure below compare the average translational movement along each axis for all three markers during a trial. The trials were then averaged by phone size for all three markers (see Figure 30). The variability of each marker was heavily influenced by phone size for all 3 axes. The inter-quartile range (IQR) of the Note phone (largest) far exceeded the other phones however the median was near the lower end of the IQR in every case, meaning the variability of movement person-to-person became more significant above the median.

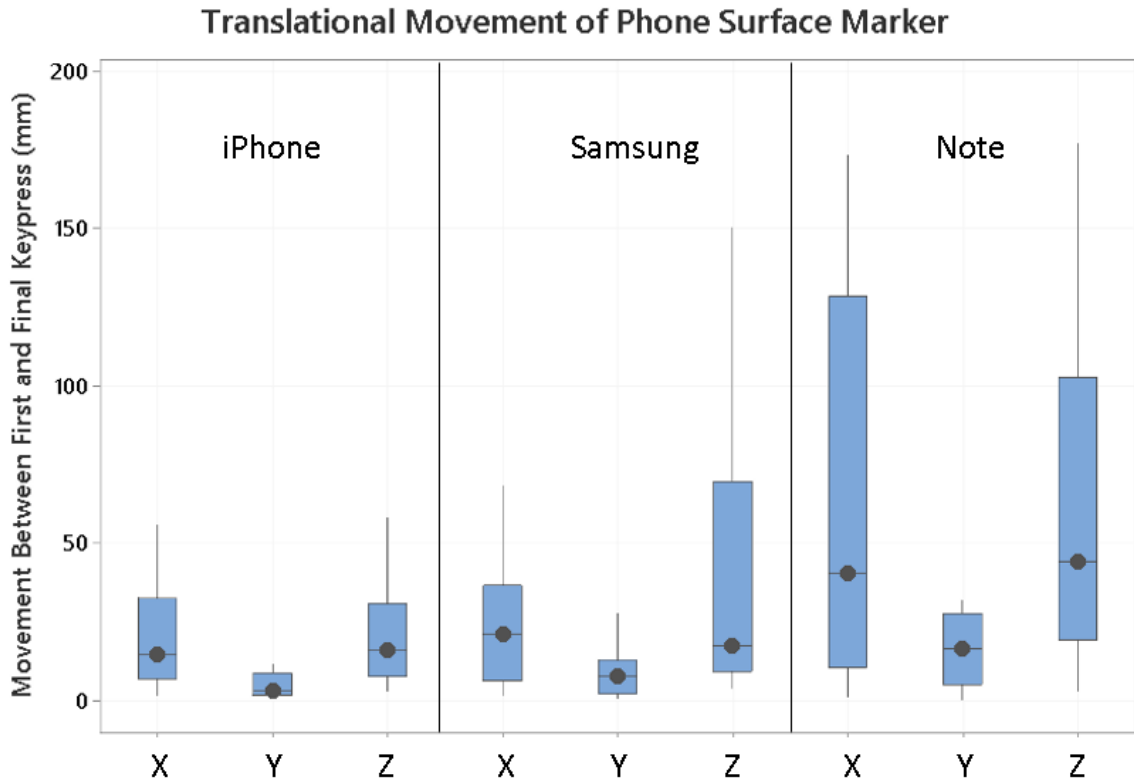


Figure 30: Phone Translational Variability Along X, Y, and Z Axes

More variability was seen on the X and Z axis than the Y axis, meaning that the phone as a solid body did not move much towards or away from the participant's body but moved more side-to-side or up-and-down. This corroborates the findings of the phone rolling along the X-axis (side to side) and pitching in the Z (up and down). Yaw had relatively very low variability, meaning while texting the wrist had very little abduction or adduction at its joint. There was no significant difference for the Limb Loss group compared to the control or by sex. The differences seen between markers were minimal. Perhaps in another study the phone markers used to create the plane should have one marker on the centre line of the phone and the other two on the far and close sides as well (as opposed to clustered near the centre line). This would have captured more roll, pitch and yaw at the phone edges, and therefore would be easier to analyze

close vs far side phone stability. It is expected that this adjusted marker layout would reveal the far side of the phone moves more as the fingers help guide the thumb to its target on the mimicked keypad.

## **4.2 Phone Size**

### **4.2.1 Forces and Phone Size**

Since three phones of different sizes were used in the study one might expect changes in the force applied to sensors to be dependant on the thumb's reaching ability or its angle of contact. It was previously established that there were no thumb angle differences between the Limb Loss and Control group, and females had flatter thumbs only on the iPhone at the top-far side and bottom-close side force sensors. This means it is likely that changes in thumb forces were not due to thumb angles but perhaps the phone size itself. To begin, a comparison of the individual force sensors on all three phones was done. Overall higher forces were seen in the Limb Loss group with significant differences in force between the groups at force sensors B and E of the iPhone ( $P < 0.05$ ), and B of the Samsung ( $P < 0.05$ ). No significant difference was found in the largest phone (Note) even at Force Sensor C where the Limb Loss group averaged 3.12 N higher than the control group ( $P = 0.165$ ) (see Figure 31).

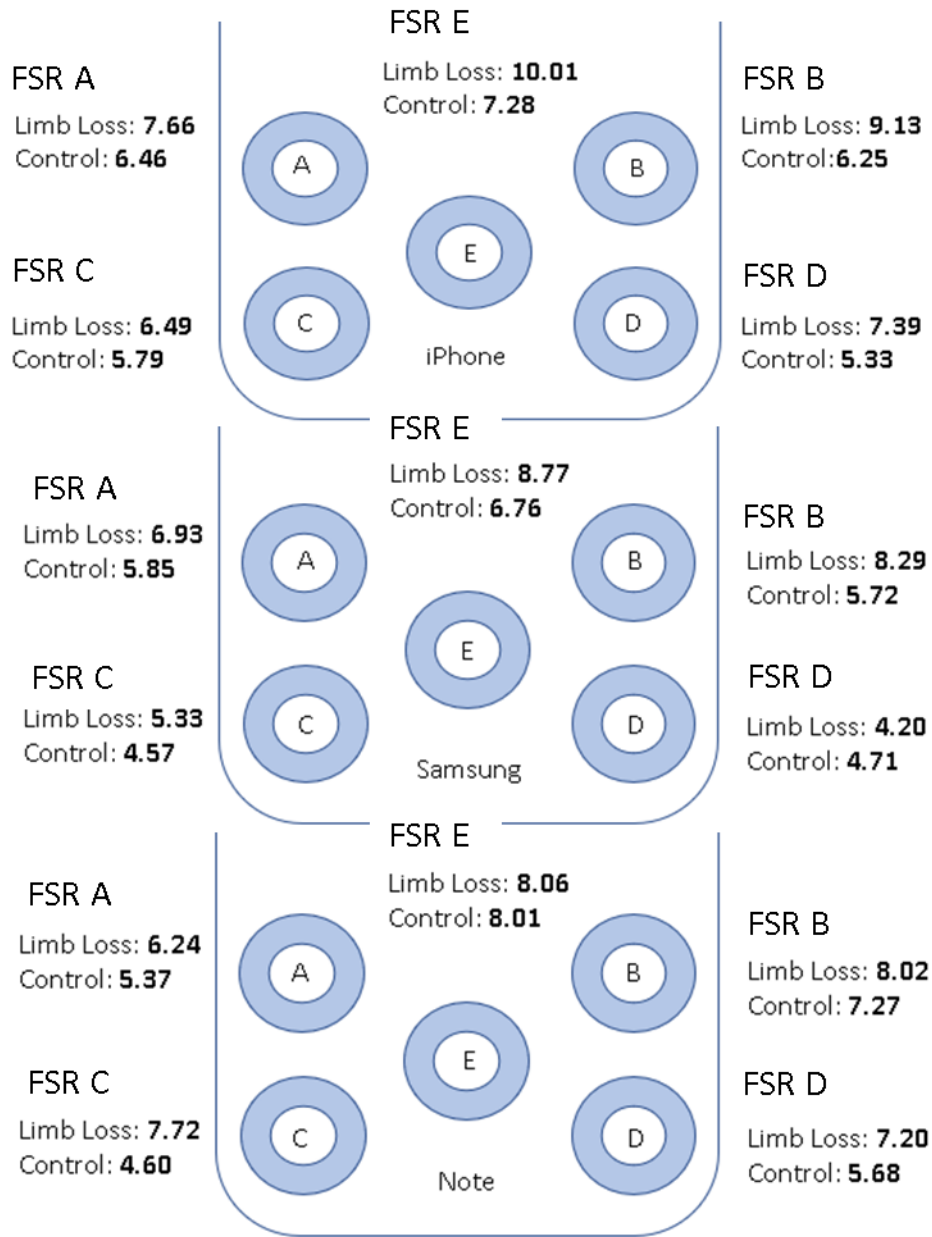


Figure 31: Force Sensor Force Comparison for Limb Loss and Control group in Newtons for All Three Phones

The forces phone-to-phone at force sensors were similar except for one instance on the Samsung phone at Force Sensor D (bottom-close side) where the Limb Loss group had lower forces than the same force sensor on the smallest ( $P < 0.01$ ) and largest

phones ( $P < 0.05$ ). It is difficult to explain why this would occur on only the mid-sized phone but is likely due to population size.

A few other observations can be made from the force location data (see Table 7). Top force sensors experienced more force than bottom force sensors. Close side force sensors experienced higher forces than far side force sensors on the largest phone (the Limb Loss group did not follow this rule on bottom force sensors). Central force sensors were always the largest force locations.

Table 7: Comparing Top vs Bottom and Close vs Far Side Forces on Phones All

Participants

Phone	Top-Close Side vs Bottom-Close Side (force ratio)	P - Value		Top-Close Side vs Top-Far Side (force ratio)	P-value
iPhone	<b>1.19</b>	0.014		1.04	0.244
Samsung	<b>1.42</b>	0.004		1.05	0.268
Note	<b>1.22</b>	0.001		<b>1.33</b>	0.002

Forces were higher on the top-close side for the Note and top force sensors, but they were not dependent on thumb angles, sex, limb status, or phone size. A continued analysis for why higher forces were present in the Limb Loss group and other participants on a case-to-case basis can be found in sections 4.3 "Forces and Timing" and 4.4 "Hand Anthropometrics".

#### 4.2.2 EMG and Phone Size

For every reaction force following an abduction of the thumb (moving away from the thumb's base) there was an EMG response preceding it. Muscle activation peaks cannot be compared person to person as EMG amplitudes can be inconsistent due

to line noise, muscle artifact, skin moisture, muscle depth, and other factors, however EMG peaks can be compared on a phone-to-phone basis

The abductions are denoted in the figure (Figure 32) by E to A, B to C, and D to E; these are the type of thumb movement being performed as the muscle activation occurs (the pattern repeats twice). Force sensor readings are the solid lines F1 to F5 and the EMG is the dotted line. When the distance in time elapsed from the filtered EMG peak to the corresponding force peaks were analyzed, some information was found.

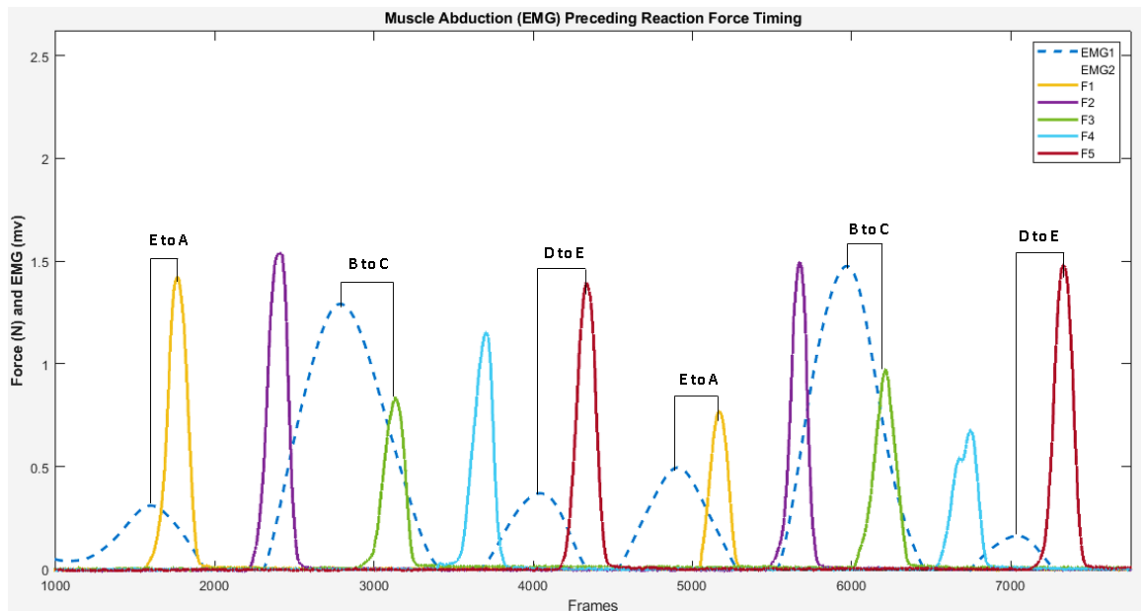


Figure 32: Time Between Thumb Abduction Muscle Activation and Following Reaction Force

Firstly, any movement of the thumb abduction from force sensor B to C (see Figure 33), the longest movement in the pattern, yielded longer times required to complete the movement overall. Secondly, in each abduction case there was a significant increase in time required to complete a movement as phone size increased for abduction movements E to A and B to C. Lastly, the final abduction in the pattern (D to E), where

the thumb moved from the bottom-close side force sensor to the central one had the least amount of change in muscle activation time. This was due to the thumb not needing to reach to the far side (like in E to A and B to C) but rather return to a neutral position at the centre of the keypad area.

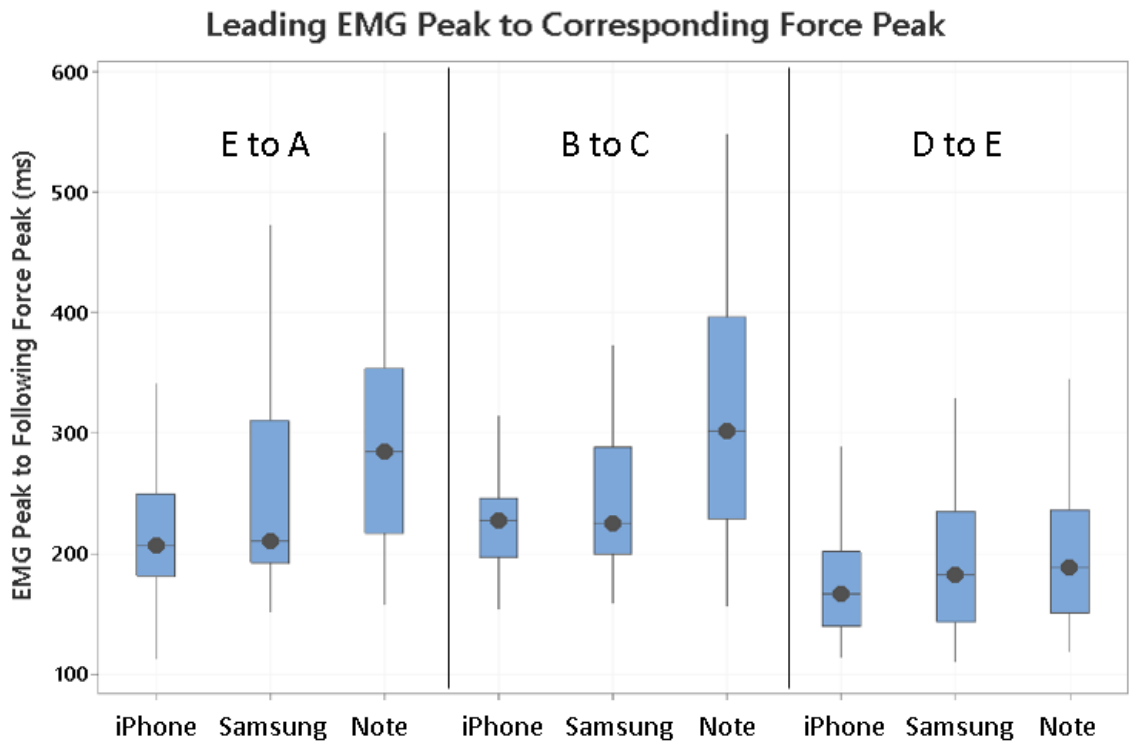


Figure 33: Muscle Activation Time to Corresponding Force Peak Movement and Phone Comparison

Muscle activation was significantly higher on the largest phone when compared to the medium phone ( $P < 0.01$ ) averaging 0.65 mv higher (see Figure 34). The peaks of the small and medium phone were also found to be significantly different with the smallest phone's mean EMG being 0.35 mv lower ( $P < 0.05$ ).

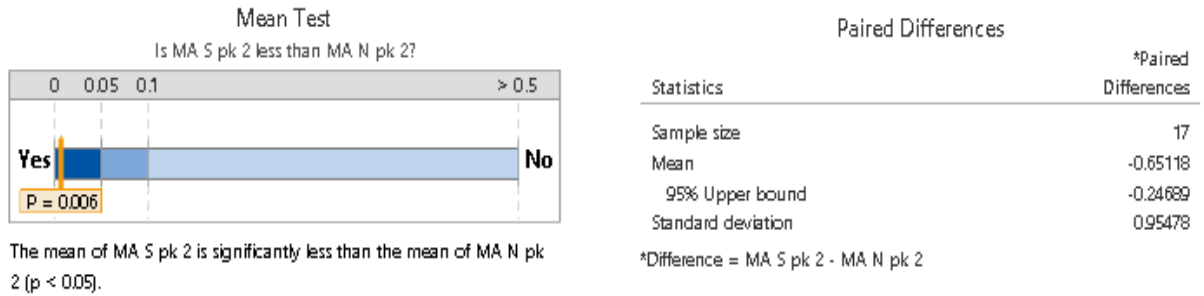


Figure 34: 2 Sample T-test for Muscle Activation and Phone Size (Samsung and Note example)

#### 4.2.3 Pattern Completion Time and Phone Size

Two-handed texting provided stability needed to text more efficiently. The control group's one-handed and two-handed pattern completion times were compared (see Figure 35).

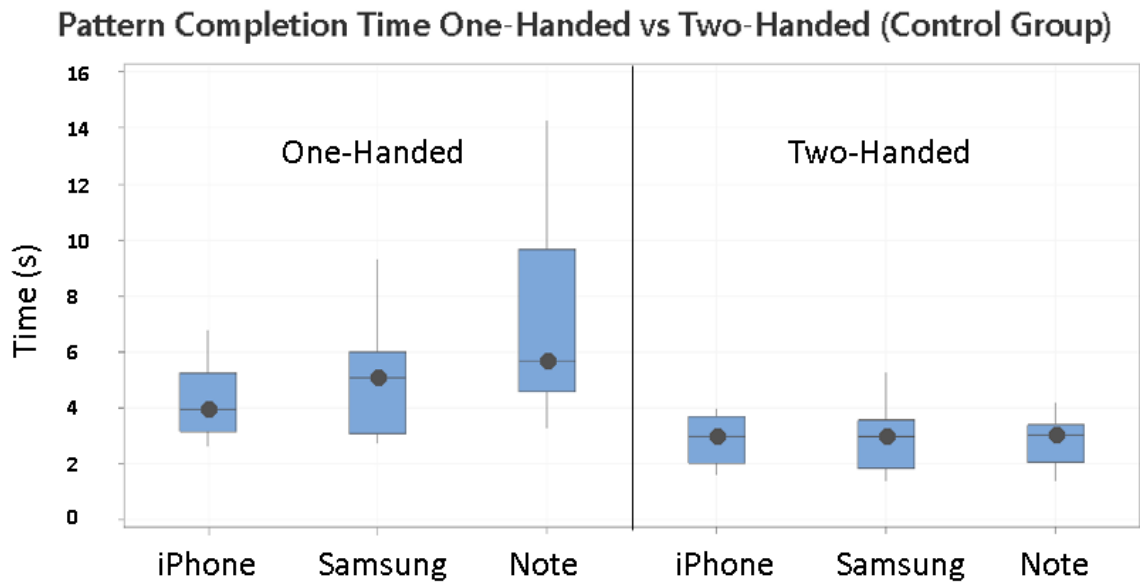


Figure 35: Pattern Completion Time One and Two-Handed Comparison

When texting two-handed the control group improved their texting efficiency on each phone size (iPhone, Samsung, Note, all  $P < 0.01$ ). The increase in pattern

completion time one-handed for the smallest to largest phone were 0.94, 2.08, and 2.67 seconds on average respectively. As the phone's size increased, one-handed texting time increased, and two-handed texting stayed the same. It is reasonable to assume that an increase in phone size leads to more time required in one-handed text messaging, and prolonging texting may increase the risk of RSI.

Pattern completion times were significantly higher on all phone sizes for the Limb Loss group ( $P < 0.05$ ) (see Figure 36). At this point in the report the key differences between the Limb Loss and control group were higher pain and higher forces for Limb Loss. Neither directly explain why the Limb Loss group would require such a significant amount of time longer to complete patterns but will be analyzed further along in this report.

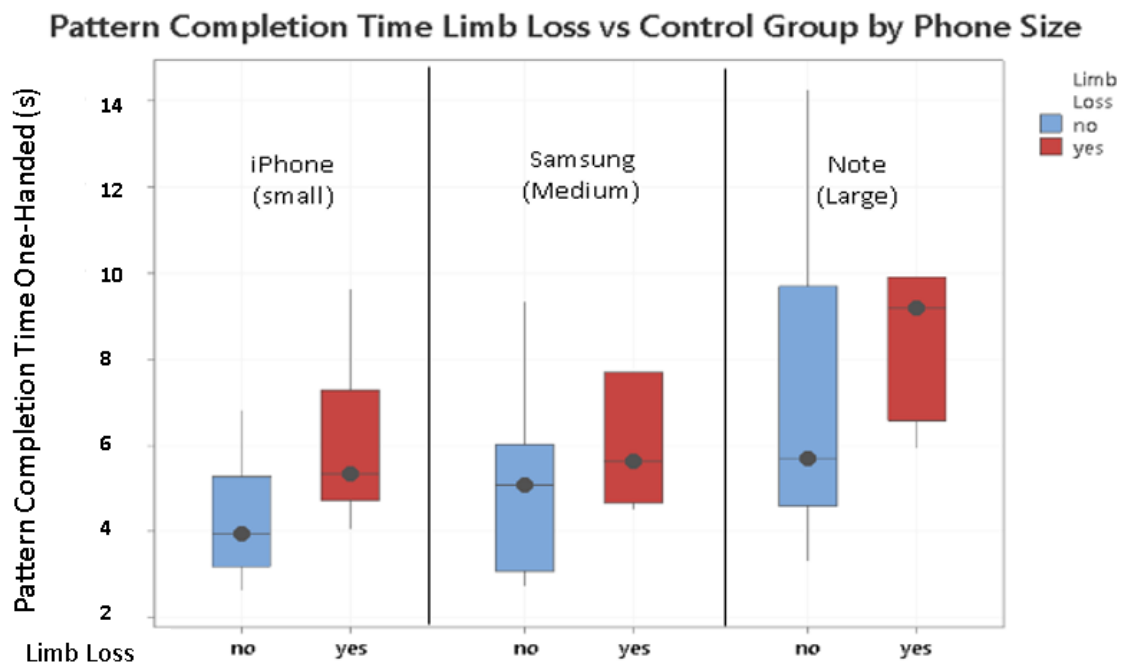


Figure 36: Pattern Completion Time Limb Loss and Control Group Comparison by Phone Size

#### 4.2.4 Thumb Distance Travelled

Tracking and analyzing thumb movement was done using the motion capture data, specifically the distal marker of the thumb and the phone markers. To track thumb distance travelled it must be done with respect to the phone, therefore at each frame of data a singular marker on the phone surface was translated to the origin and the thumb marker was then translated the same distance and direction. After this one frame of movement was then calculated for the thumb's movement. These steps were then repeated for the duration of the trial (between the first and the final force sensor press in the pattern). Each movement distance was loaded into an array and the sum of this thumb distance array is the total distance of thumb travel (see Equation 3).

Equation 3: Thumb Marker Tracking and Total Thumb Movement Distance

$$d(P_n, P_{n-1}) = \sqrt{(x_n - x_{n-1})^2 + (y_n - y_{n-1})^2 + (z_n - z_{n-1})^2}$$

$$\textit{Total Thumb Distance Travelled} = \sum_n d(P_n, P_{n-1})$$

The following table compares the average thumb distance travelled of a trial on each phone and the baseline distance of the corresponding phone size. The baseline distance is the minimum distance the thumb would require pressing each force sensor in the pattern twice. This comparison was made for one-handed texting (see Table 8). Distance added can be assumed to be from lifting the thumb off the phone surface as very few thumbs deviated from the intended pattern path, and the few instances they did were not included in the averaging.

Table 8: Thumb Distance Travelled

Phone	Baseline (mm)	Thumb Distance Travelled (mm)	Thumb Distance Travelled St. Dev (mm)	Difference (mm)
iPhone	314	461.1	102.1	147.1
Samsung Galaxy	432	545.0	92.2	113
Samsung Note	533	660.5	108.8	127

What can be discerned from this comparison is that using the small iPhone led to participants lifting the thumb further off the screen surface while reaching to the next force sensor by a significant amount ( $P < 0.05$  v. Samsung,  $P < 0.05$  v. Note). The iPhone averaged an additional 147 mm of thumb travel during a trial. When the thumb was required to reach further on larger phones, the thumb did not appear to lift as much.

No significant difference was found between the Limb Loss and control group on the iPhone, Samsung or Note phones for thumb distance travelled. No significant difference was seen between sexes on the iPhone or Samsung, however, the Note phone showed female thumbs averaged 114 mm more thumb distance travelled ( $M = 637\text{mm}$  and  $F = 751\text{mm}$ ,  $P < 0.05$ ).

#### 4.2.5 Thumb Velocity

It was expected that thumb velocity would be influenced by phone size. Phone size did not influence thumb velocities. The average thumb velocity was calculated by dividing the thumb distance travelled between force sensors (relative to the phone) by the time elapsed between force peaks. Movement types E to A and D to E were the same movement type (extension/abduction) and had the same distance between force sensors, likewise for A to B and C to D (flexion/adduction). Performing thumb movements from

Force Sensors B to C (abduction) had higher velocities, this was the longest movement in the pattern and reside in the furthest right box in Figure 37. A to B and C to D movements from the far side to the close side of the phone (flexion/adduction) are in central box and were the second longest movement in the pattern. The far-left box contains thumb extensions/abduction from E to A and D to E, the shortest and slowest movement in the pattern.

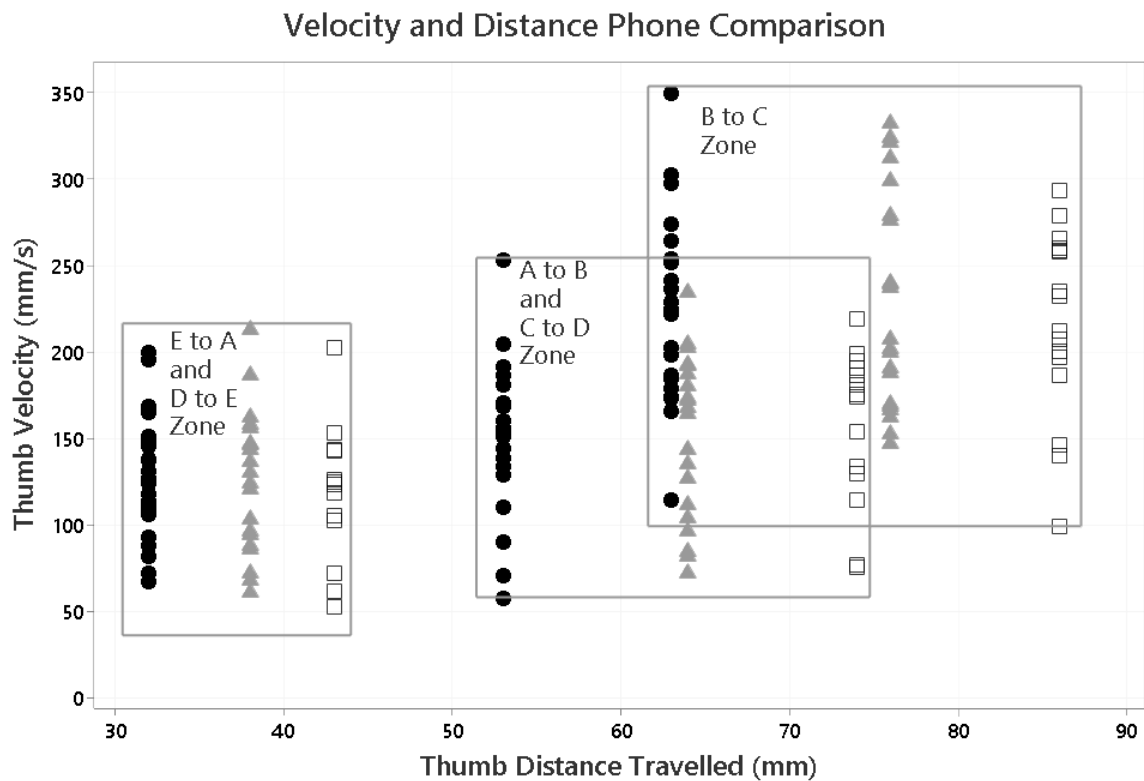


Figure 37: Thumb Velocity and Phone Size (Circle – Small, Triangle – Medium, and Square – Large Phone Sizes)

The iPhone are the black circles, the Samsung are the grey triangles, and the Note phone are the white squares for reference. This means thumb velocities did not change with the phone's size adding distance between force sensors, but rather the distance in tandem with the type of movement being performed. Paired t-tests revealed

thumb velocities were significantly higher for the B to C abduction than both the adduction (A to B, C to D) and extension (E to A, D to E) movements ( $P < 0.05$ ,  $P < 0.01$ ). No significant difference was found between A to B (or C to D) and the E to A (or D to E) movements although the mean was slightly higher.

### 4.3 Forces and Timing

#### 4.3.1 One and Two-Handed Texting

It has been established that two-handed texting is beneficial towards texting mechanics in a few ways, specifically stability and text completion time. Table 9 compares the force sensors average force values on each phone with the one-handed data. This table includes solely the Control group as the Limb Loss group did not text two-handed.

Table 9 : Forces in Newtons of One and Two-handed Texting at Force Sensors for Control Group

Phone and Force Sensor	One -Handed	Two-Handed	Difference
iPhone A	6.46	6.87	-0.41
iPhone B	6.25	6.69	-0.44
iPhone C	5.79	5.41	0.38
iPhone D	5.33	6.28	-0.95
iPhone E	7.28	6.44	0.84
Samsung A	5.85	6.01	-0.16
Samsung B	5.72	6.35	-0.63
Samsung C	4.57	5.81	-1.24
Samsung D	4.71	5.27	-0.56
Samsung E	6.76	6.30	0.46
Note A	5.37	7.07	-1.70
Note B	7.27	7.05	0.22
Note C	4.60	4.83	-0.23
Note D	5.68	6.62	-0.94
Note E	8.01	7.47	0.54

While texting two-handed it was expected that forces would be lower at every force sensor on every phone type, however no significant reduction in force was found. In fact, 10 out of 15 force sensors recorded higher forces during two-handed texting.

### 4.3.2 Force and Pattern Completion Time

The forces and the time required to complete a pattern trial are directly related. Participants with higher forces took longer to complete the pattern for all phone sizes (see Figure 38). This was evident on all phone's and at each force sensor location for the control group. The Limb Loss group only showed notable regression above 30% on the largest phone (Note). Regression of the polynomial fits are as follows in Table 10:

Table 10 : Force vs Pattern Completion Time Regression Fits for Each Force Sensor

<b>Force Sensor Location</b>	Force Sensor A	Force Sensor B	Force Sensor C	Force Sensor D	Force Sensor E
<b>Regression %</b>	37.1	55.1	34.6	58.2	52.8

A note of interest shows that Force Sensors A and C located on the far side away from the hand show lower regression fits than the central and close side markers, and this was also true for all phone sizes. The following section on force durations in this report will detail where time is added in the pattern when higher forces are a factor (continued in section 4.3.3 Force Duration). High reaction forces do not explain why a participant would add time to their pattern completion time so further investigation is needed.

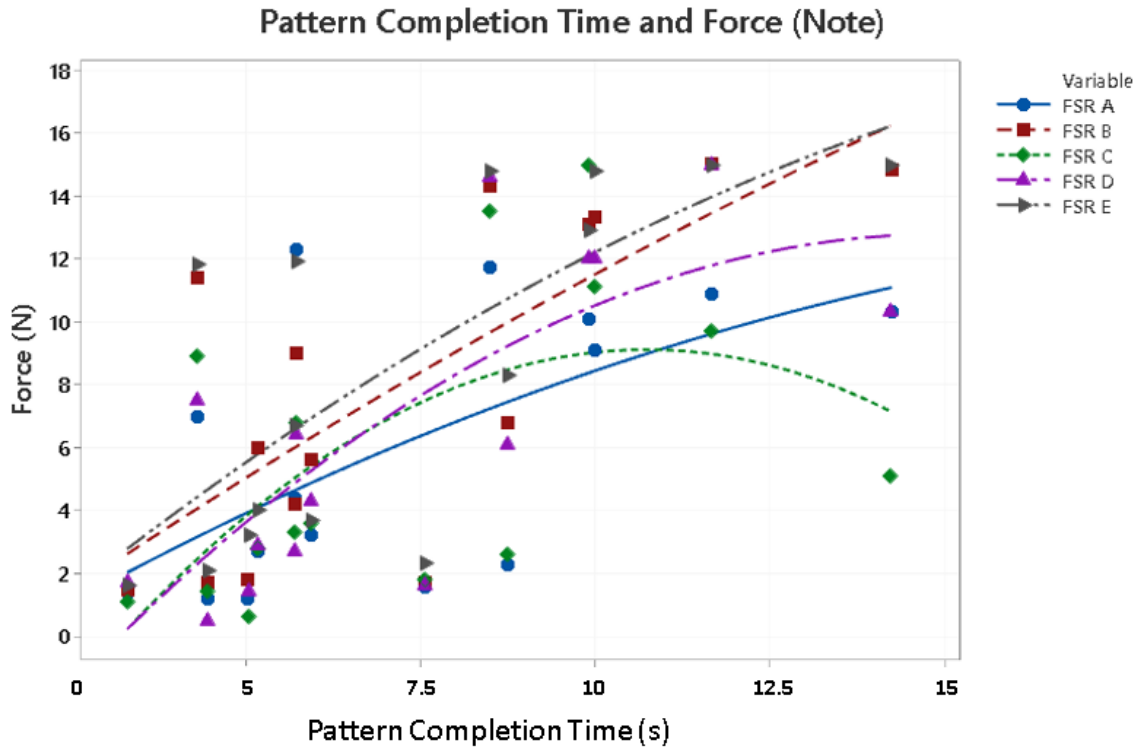


Figure 38: Overlaid Force Sensor Responses and Patten Completion Time (Note)

### 4.3.3 Force Duration

To find where time was being added to a pattern's completion time the force curves were measured at 30% of the force peak height to measure force durations relative to one another. Firstly, the durations at each force sensor location for the entire population were averaged to see if any particular force sensors are held for longer than others. It was found that one force sensor was held significantly longer than another. Force Sensor D had significantly longer keystroke durations than Force Sensor C for all phone sizes (see Figure 39 using the iPhone for example) ( $P < 0.05$ ). Force Sensor C is on the far side of the phone and Force Sensor D was on the close side. The red markers indicate an instance of a large difference.

### Paired t Test for the Mean of iPhone FSR C and FSR D Diagnostic Report

Paired Data in Worksheet Order

Investigate any pairs with unusual differences (marked in red).

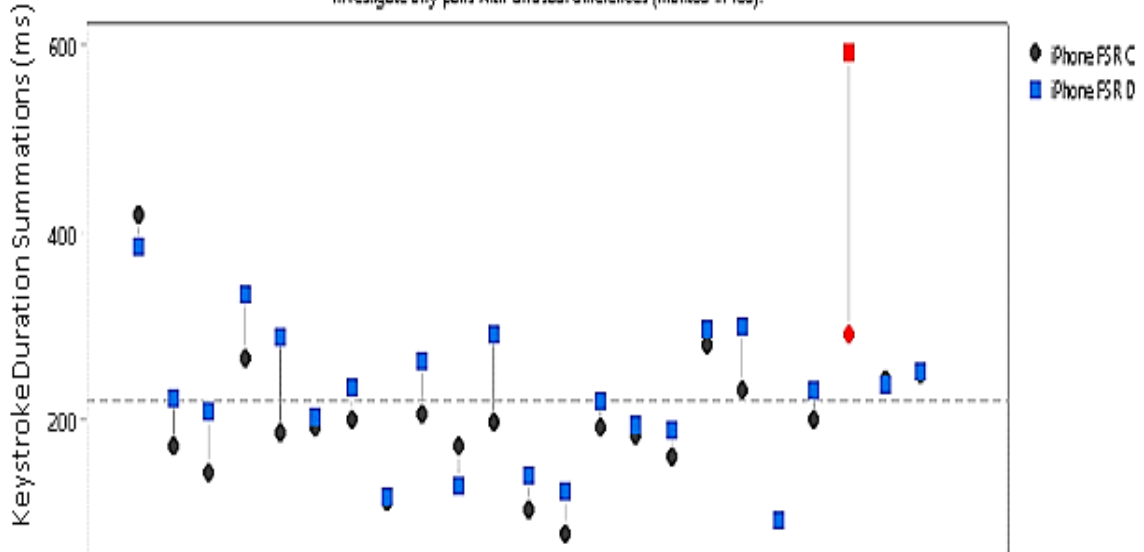


Figure 39: Keystroke Duration Differences between Force Sensor C and D

When analyzed by sex and limb status some other observations were made.

Female keystroke duration medians were longer on every phone size and force sensor location, the largest differences took place on Force Sensors C and D (see Figure 40).

The most prominent outliers were found on the medium size phone in the female group.

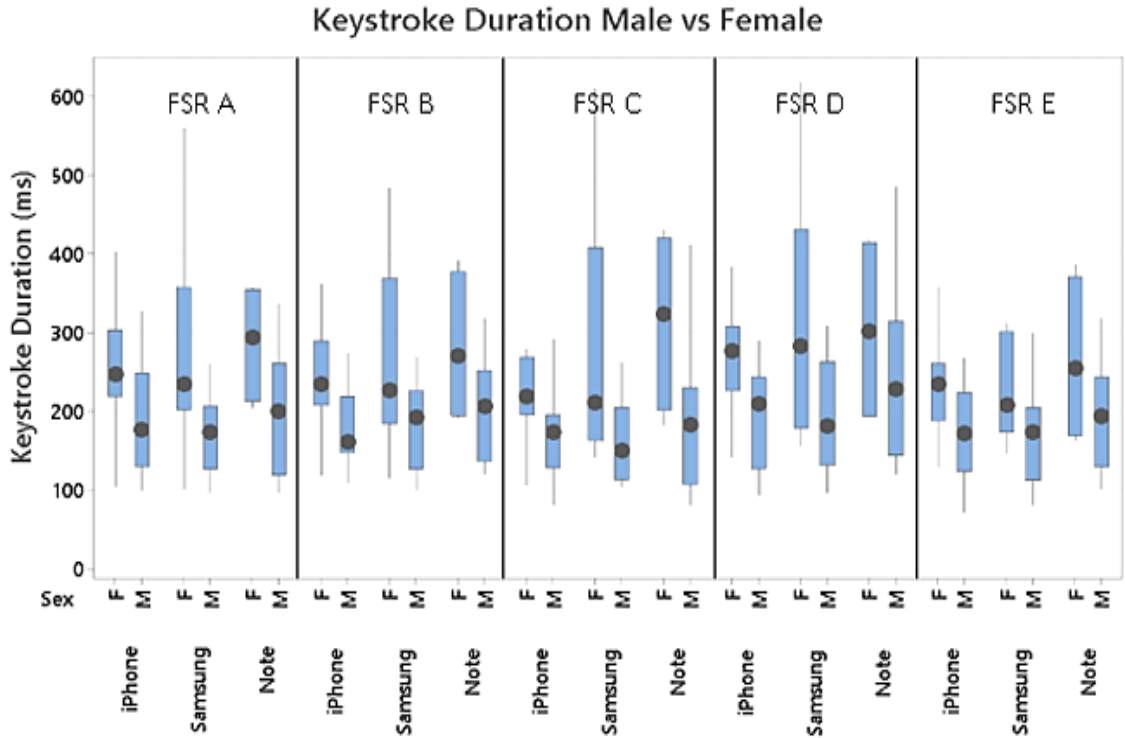


Figure 40: Keystroke Duration by Sex

A median keystroke duration plot of the Limb Loss and Control groups conveys that the Limb Loss group pressed the force sensor for longer on average than the Control group, however, in only a few instances was the difference significant (see Figure 41). Those differences were found on iPhone Force Sensor B ( $P < 0.05$ ) and iPhone Force Sensor E ( $P < 0.05$ ). Recall from section 3.3 "Forces" that the iPhone had higher overall forces on Force Sensors B and E relative to the other three force sensors.

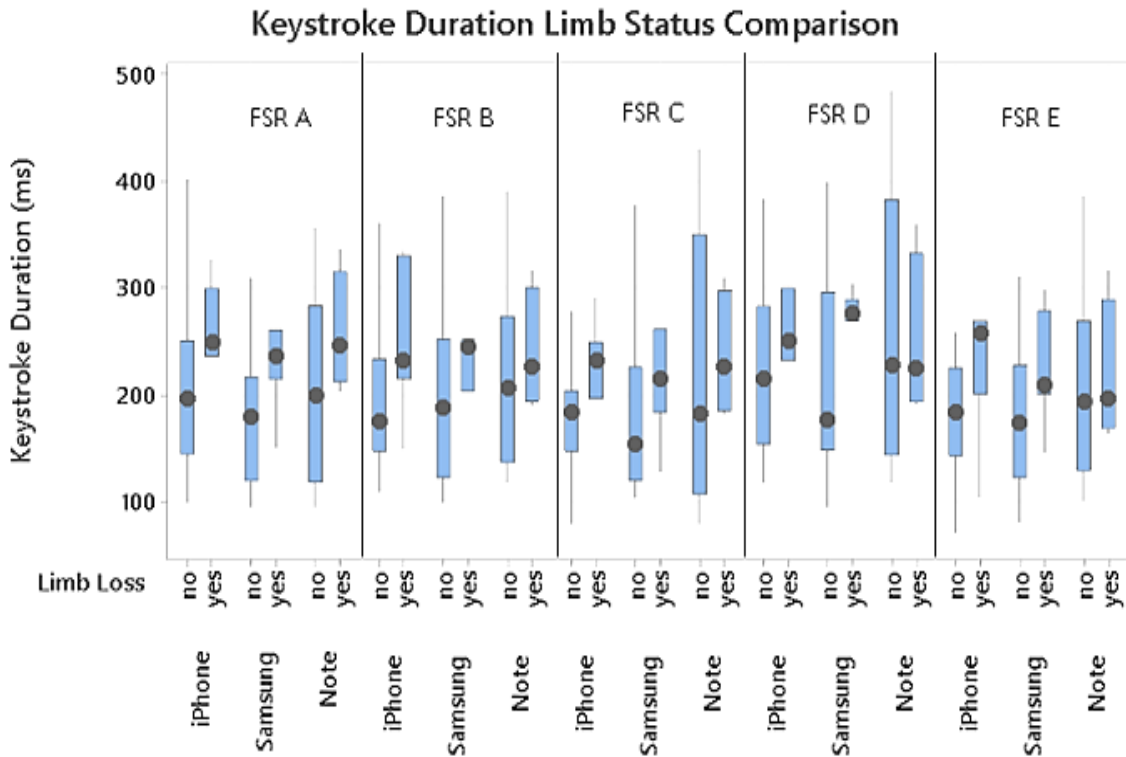


Figure 41: Keystroke Duration and Limb Loss

To expand on texting mechanics and the relationship with keystroke duration, the reaction forces were evaluated alongside the corresponding force durations (see Figure 42). The left panel is the Control group, and the right panel is the Limb Loss group. Both sets of regression curves show that as keystroke duration increases so do forces. R-sq values of the control group range from 52.1% to 67.4% while the Limb Loss regression ranged from 50.0% to 93.3%. For this population size these should be regarded as strong regressions. In the figure it appears that two cluster groups of data points are formed, arbitrarily forming a high and low force group above and below the 6 N mark. The difference in the summation of keystroke durations (Force Sensors A through E) of participants in the high and low force groups averaged 8.26 seconds, a significant difference of time required to complete these sets of keystrokes.

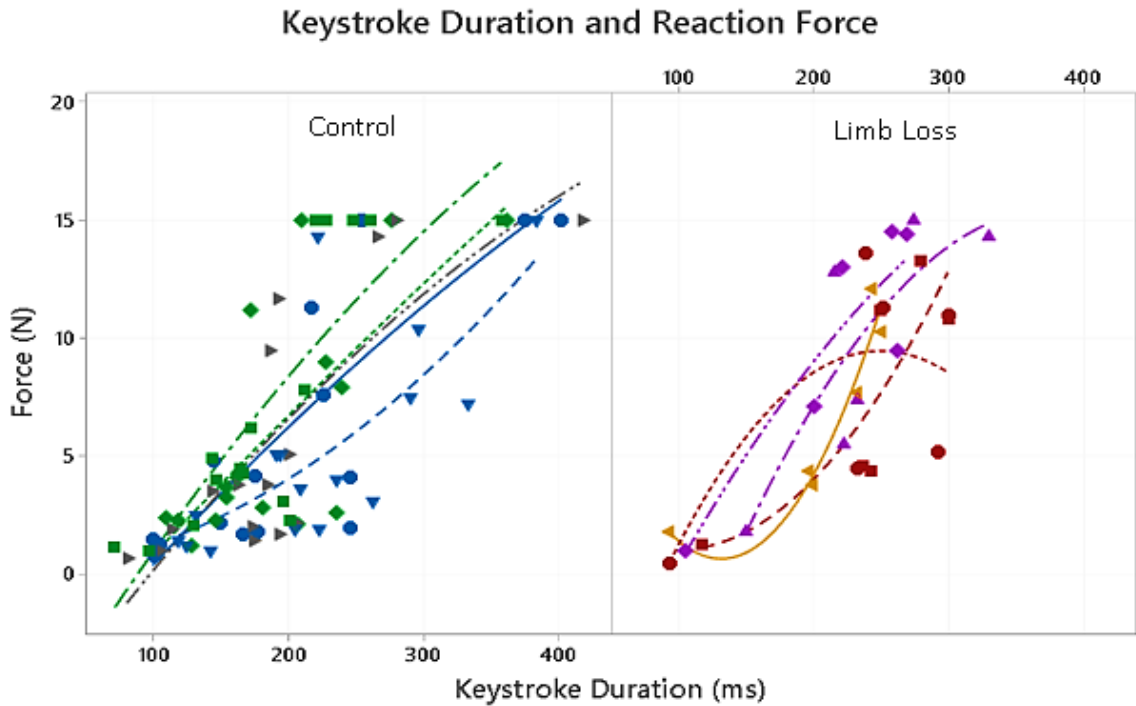


Figure 42: Keystroke Duration and Force

With all this information regarding keystroke durations and forces, the following observations were made. Females pressed and held keys for longer than males, and central and close side key locations were held for longer than far side keys. The Limb Loss group held longer on the iPhone's central and top-close side keys. Higher reaction forces added an average of 0.86 seconds per key press, potentially adding 8.6 seconds of extra time to their trials (10 keys are pressed per short pattern trial). This was similar to the time difference seen when separating high and low force groups, 8.26 seconds. This is concrete evidence that spending longer pressing on the force sensor increases the forces experienced by the thumb and time required to text, both of these being factors that may lead to RSIs.

#### 4.3.4 Force Variability

Another measure of phone control was conducted by finding the variations in force peaks on different phone sizes. Variation was calculated using mean absolute deviation at each force sensor location (see Equation 4), where  $n$  was the number of values,  $m$  the mean, and  $x$  the values (see the sketch in Figure 43). Each one-handed trial was averaged and then compared to their corresponding force average.

Equation 4: Mean Absolute Deviation Formula

$$\frac{1}{n} \sum_{i=1}^n |x_i - m(X)|$$

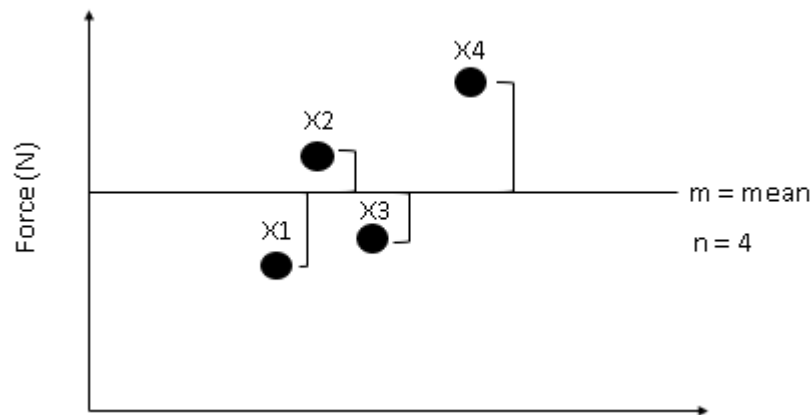


Figure 43: Sketch of Mean Absolute Deviation

Force variation and force applied to the sensors were directly related.

Participants with higher forces saw more variation in forces and this was perhaps related to instability of the phone (see Figure 44). This occurrence was seen on all phone types during one-handed texting while two-handed texting saw very little variation at all. The

regression of Force Sensors A through E using quadratic curves (these can be thought of as lines of best fit) are as follows (see Table 11):

Table 11: Regression at Force Sensors for Force Variability and Thumb Force

Force Sensor Location	Force Sensor A	Force Sensor B	Force Sensor C	Force Sensor D	Force Sensor E
Regression Percentage	45.0	46.1	56.4	62.1	47.1

For this population size it is considered a strong relationship, especially since the trend is true on every force sensor. There is a distinct cluster of low force variability and low forces below 4 Newtons but above that there are irregularities.

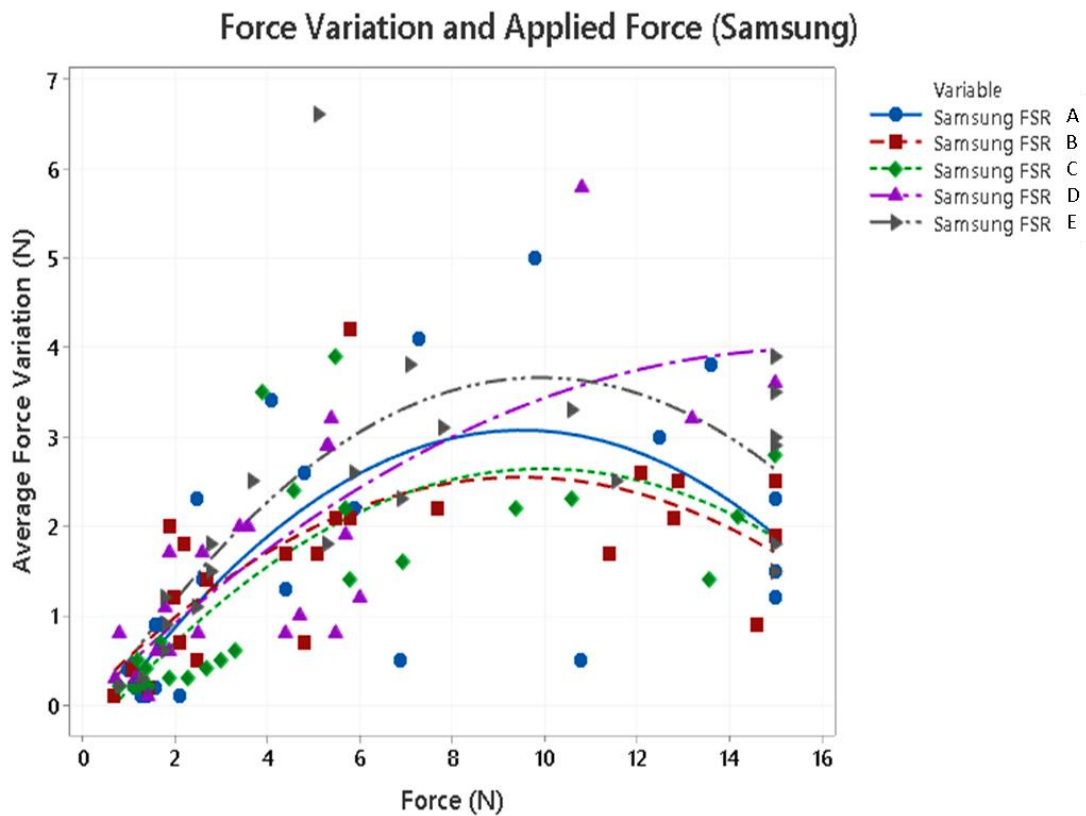


Figure 44: Force Variability and Applied Force Example

The most difficult force sensor to reach throughout the experiment trials was the bottom-far side force sensor on the Note phone as it often required the thumb to extend far from its neutral position. Figure 45 below shows that wider hands had fewer issues pressing the bottom-far side force sensor with a consistent amount of force.

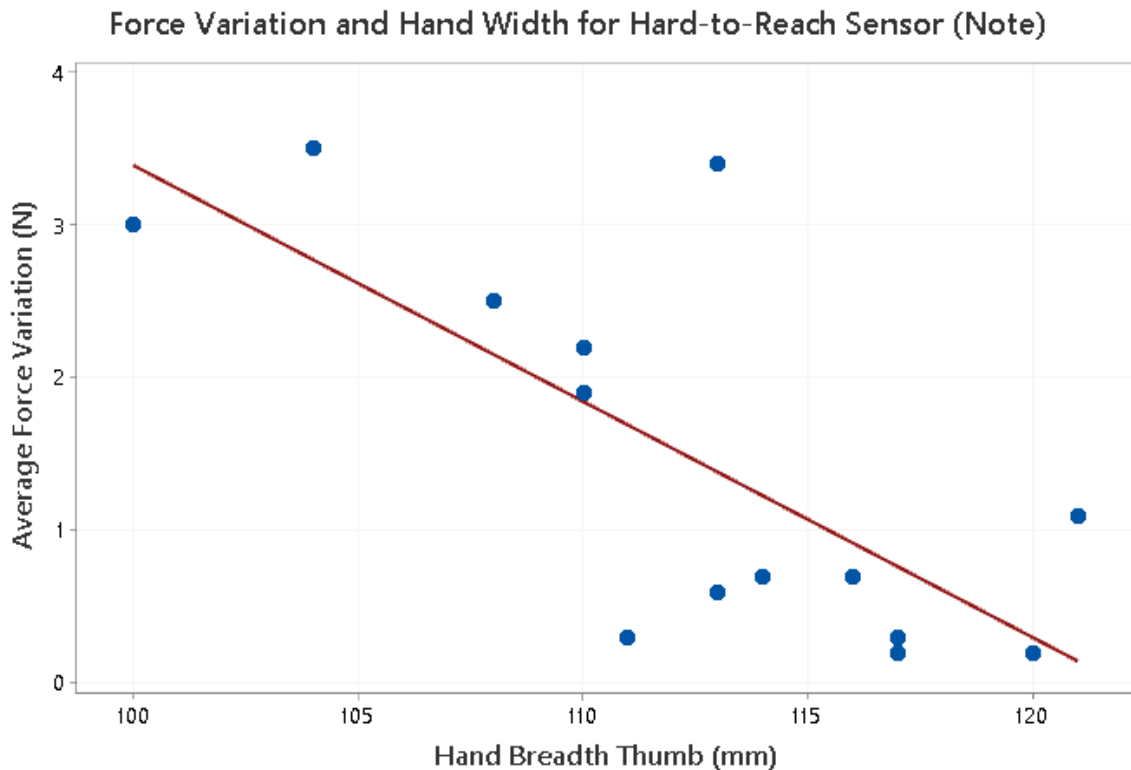


Figure 45: Force Variation and Hand Width on Hard-to-Reach Sensor

Surprisingly, no significant difference was found when force variation and hand size were compared for any other force sensor location. No significant difference was found when comparing pattern completion times and force variation. Force variation and force duration was also analyzed, and no relationship was found.

## 4.4 Hand Anthropometrics

### 4.4.1 Hand Size and Force

A 2-sample t-test was administered to hand sizes that determined the male population of this study had larger hands, an increase of relatively the same mean in length and width (diff: 16 mm, 11mm,  $P < 0.01$ ) (see Figure 46). This difference in hand size was relevant to both thumb forces and texting efficiency. There was no significant difference in hand size for the Limb Loss and the Control group (see Figure 47). In the analysis portion of this report, hand size was compared with thumb forces, effect of phone size, EMG, and texting efficiency.

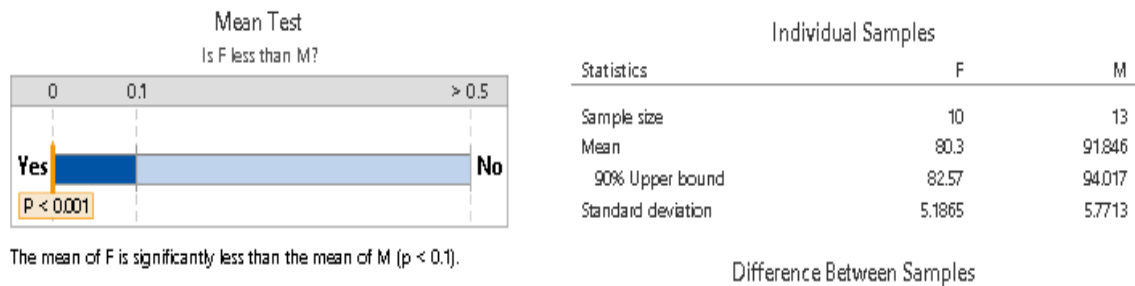


Figure 46: Difference in Hand Width by Sex (Made in Minitab)

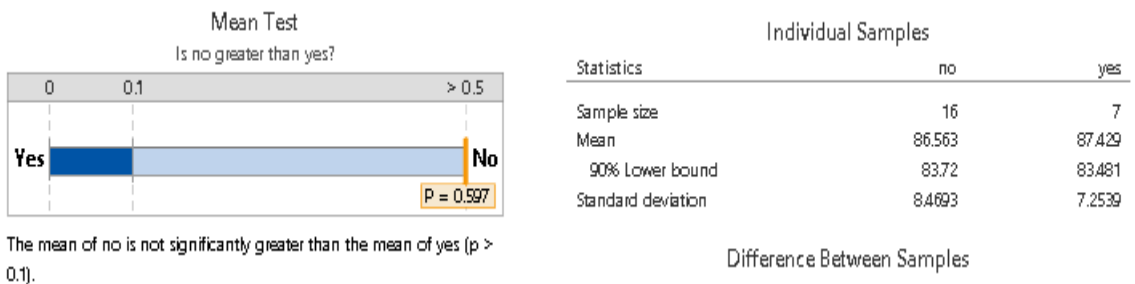


Figure 47: No Difference in Hand Size by Limb Status (Made in Minitab)

Hand size influences texting mechanics. Larger hand lengths and hand breadths lead to lowering forces on bigger phones. When overlaying individual force sensor data it was apparent on all phones that forces decreased with increased hand measurements of any kind (see Figure 48). The strongest regression was found on the Note phone and could be related to larger phones being more stable in bigger hands (see Table 12). Participant 23 (a person with limb loss) was excluded from this scatterplot as almost all their recorded forces were above the 15 Newton threshold of the instrumentation.

Table 12: Regression at Force Sensors for Hand Width vs Thumb Force on Note Phone

<b>Force Sensor Location</b>	Force Sensor A	Force Sensor B	Force Sensor C	Force Sensor D	Force Sensor E
<b>Regression %</b>	32.1	45.2	35.3	35.0	51.0

These regressions were marginal but would likely be stronger with a larger population based on the distribution and consistency seen on all phones and force sensors. Again, it is seen that the regression appears on every force sensor and should be considered as a strength to the relationship.

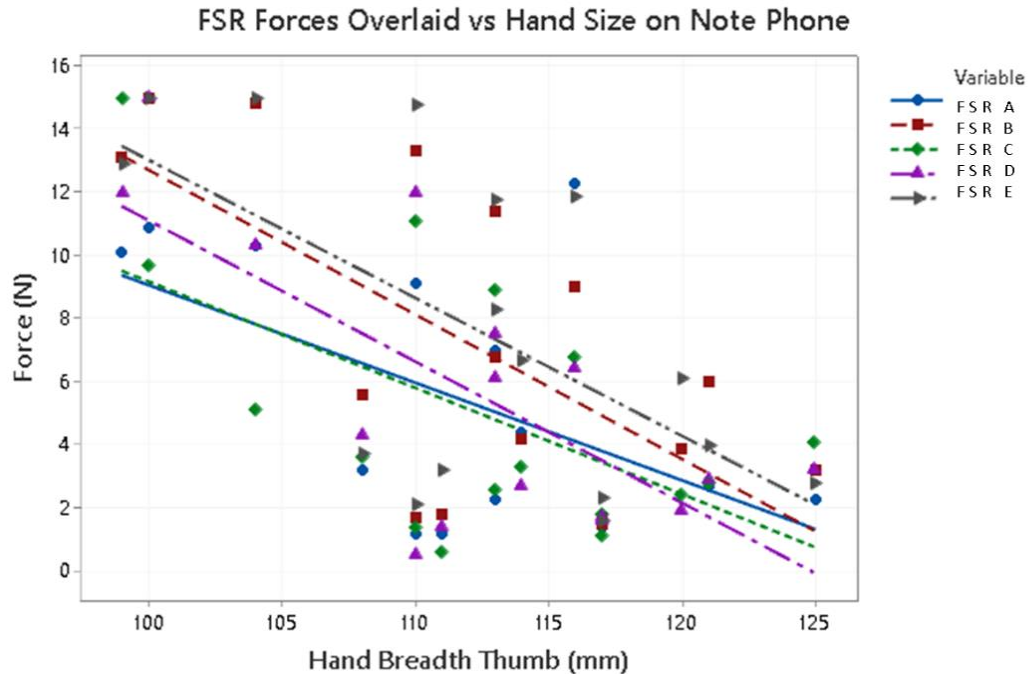


Figure 48: Hand Breadth and Force

#### 4.4.2 Hand Size and Texting Efficiency

Previously in section 4.3.3, a longer pattern completion time was influenced by how long keystroke durations were and how much force was applied to the force sensor. It has now been established that larger hand measurements yielded lower forces on all force sensor locations as well. Hand measurements were analyzed in scatter plots to find any relationships between hand sizes and pattern completion time. Pattern completion time was only slightly faster with larger hands on the Samsung and Note phones, but the iPhone showed no relationship except for hand breadth measurements. The regressions of the three phones for comparing hand width (across the thumb) to pattern completion time can be seen in Figure 49 below (iPhone R-sq = 26.4%, Samsung R-Sq = 45.3%, Note 24.3%). Pattern completion time may be marginally influenced by hand size, but a

larger population study would be needed for further evidence as these regressions are fairly low.

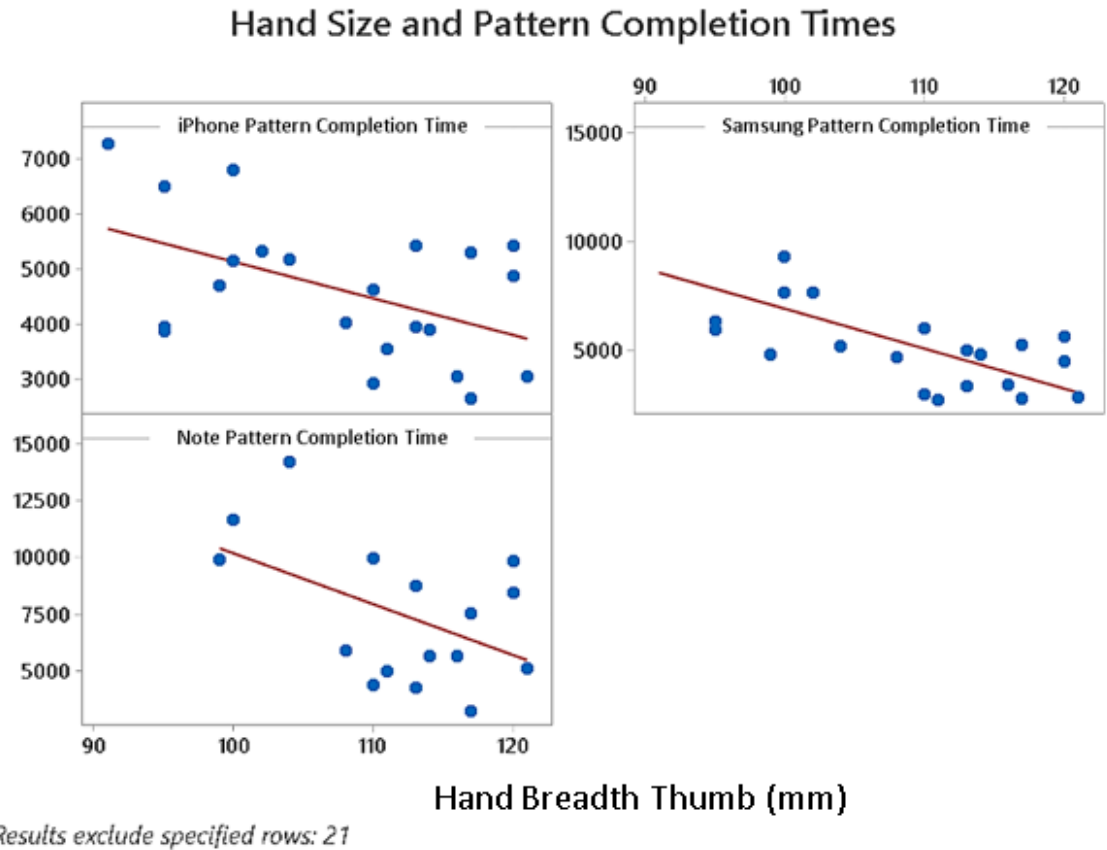


Figure 49: Hand Size (Hand Breadth Thumb) and Pattern Completion Time (ms)

While analyzing hand size's relationship to pattern completion time, it was also important to determine if hand size had an effect on thumb speeds or if it was dependant on other factors. Each participant's average thumb movement velocity in the pattern was analyzed next to each hand measurement and there were no significant relationships found on any device type. Hand size does not appear to have any effect on thumb speeds (see Figure 50).

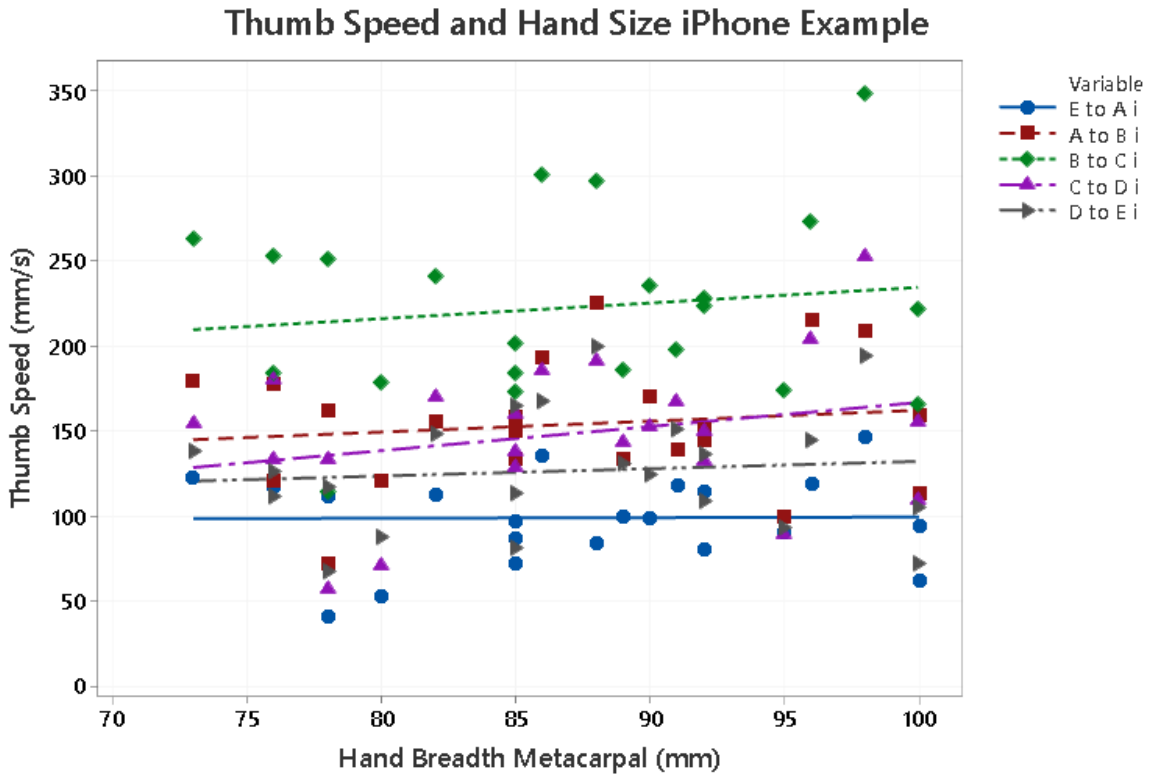


Figure 50: Example Plot of Thumb Speeds and Hand Size (using iPhone)

Hand Size had a marginal effect on EMG muscle activation during two out of three abductions seen in the pattern (E to A and B to C) but only on the iPhone and Samsung phones. Recall that abduction movements E to A and B to C had higher muscle activation than D to E (section 4.2.2) and were faster than D to E as well (section 4.2.5). Larger hands on these phones had lower muscle activation. This may demonstrate an advantage for larger hands being able to reach towards far side force sensors with less effort. The linear regression fits of Figure 51 (below) are as follows in Table 13:

Table 13: Regression of Muscle Activation vs Hand Size

Phone Type	E to A Regression %	B to C Regression %
iPhone	45.6	28.2
Samsung	61.2	38.5

## Muscle Activation and Hand Breadth

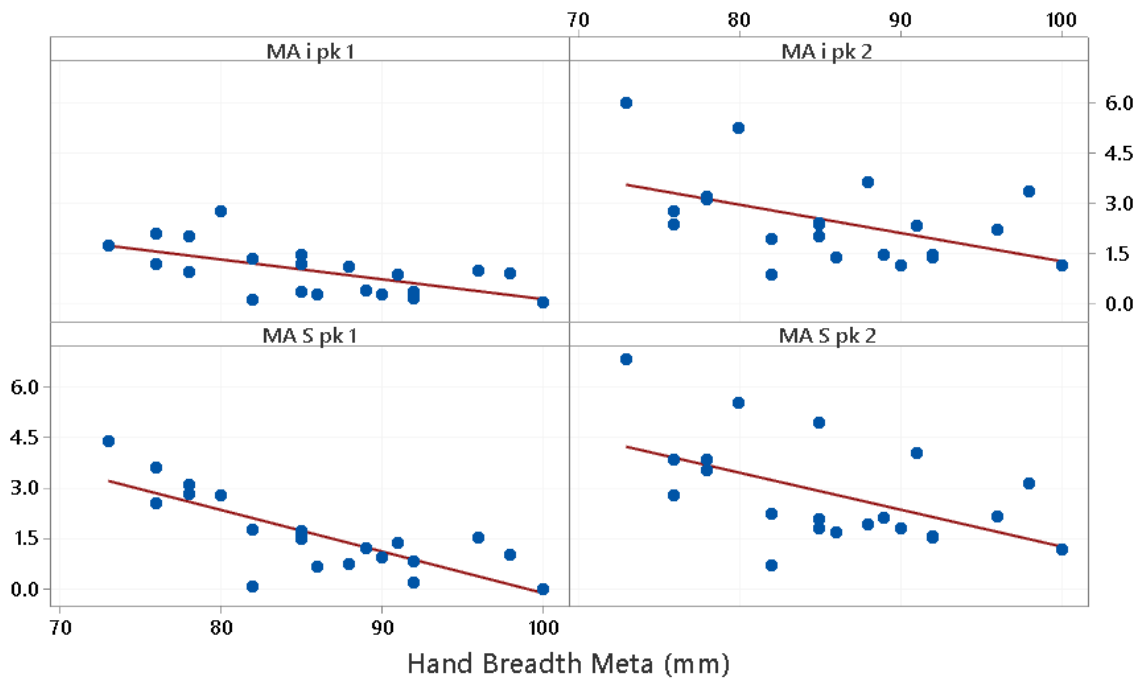


Figure 51: Muscle Activation (mv) and Hand Breadth (iPhone Top and Samsung Bottom, E to A Left and B to C Right)

One more area of interest concerning hand size and texting efficiency was the relationship of hand size and the ability to reach far side force sensors. Males with wider hands required less thumb angle extension to reach far side force sensors on the largest phone ( $R-Sq = 49.5\%$ ) (see Figure 52). Recall that in the male group wider male hands had less force variability on the largest phone (Note) when pressing the lower-far side force sensor (section 4.3.4). This was only true on the Note phone and likely due to how wide the phone is. This was a common issue seen throughout the experiment where the Note phone was too large for some participants to use at all. Five females and one male were unable to hold the Note phone during data collection.

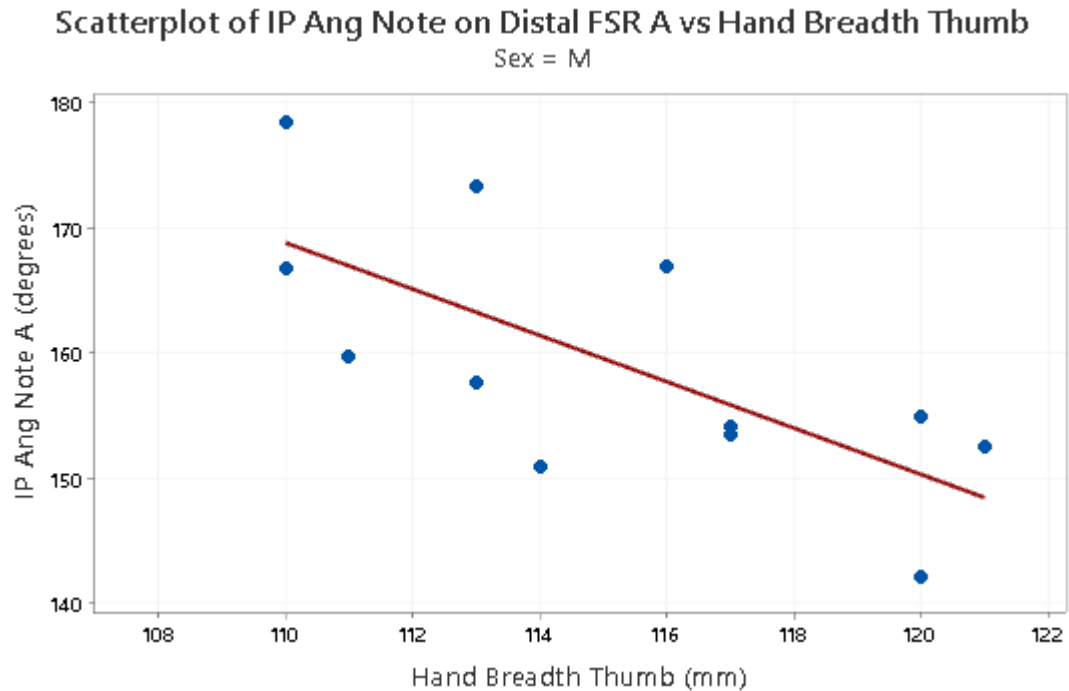


Figure 52: Reaching Ability of Males with Wider Hands and IP Thumb Angle

## 4.5 Risk Factor Assessment

### 4.5.1 Choosing Risk Variables

Risk assessments are used in the medical field to determine the likelihood of a habit, condition, or other health issue in a population. The methods used in section 4.5 were generated with help from *Analytic Methods in Maternal and Child Health* by Handler A., Rosenberg D, Monahan C., & Kennelly J. of the Maternal and Child Health Bureau, published by HRSA, 1998. Two types of risk assessment calculations were used for the current study, Relative Risk and Attributable Risk. Rosenberg et al. describe relative risk as "a measure of the strength of the association...between a risk factor and an outcome" and attributable risk "measure(s) the excess risk associated with the risk factor" (Rosenberg & Handler, 1998).

Choosing the variables for this risk assessment was done by selecting categories where discrepancies were seen between the Limb Loss and Control group throughout this report. As a reminder they are listed as follows: Wrist Angle, Wrist Pain, Thumb Pain, Forearm Pain, Finklestein and Phalen Test Pain, High Forces, Long Force Durations, Slow Pattern Completion Time, High Variance, and naturally using a One-Handed Texting Bias.

#### 4.5.2 Relative and Attributable Risk Factor

A risk factor chart consists of four categories. Quadrant "a" for those with Limb Loss and the condition or habit being analyzed and "b" without. Quadrant "c" is the control group with the condition or habit present and "d" without (see Figure 53). The variables  $n_1$  and  $n_2$  are total populations of the Limb Loss and control groups respectively. The variables  $m_1$  and  $m_2$  are the populations with and without the condition or habit respectively.

		Condition or Habit Present		
		Yes	No	
Limb Loss	Yes	a	b	$a + b (n_1)$
	No	c	d	$c + d (n_2)$
		$a + c$ ( $m_1$ )	$b + d$ ( $m_2$ )	

Figure 53: Risk Factor Chart (Rosenberg & Handler, 1998)

Relative Risk calculations are used to find ratios between at risk groups and a control group. Relative Risk is calculated using the following equation with reference to Figure 53 (see above, and Equation 5). If the relative risk ratio is one or lower this means that the Limb Loss group is not at a higher risk than the control group; if relative risk is 2 (for example) the posed risk of the condition or habit for the Limb Loss group would be twice as high as the control group. Table 14 displays results of the variables analyzed. Confidence intervals of 95% were calculated to ensure lower and upper bounds are more than one, otherwise the ratio is not strong enough to be definitive (see Equation 6). All Equations used in the risk factor section are per Rosenberg & Handler (1998).

Equation 5: Relative Risk Formula

$$Relative\ Risk = \frac{\frac{a}{(a + b)}}{\frac{c}{(c + d)}}$$

Equation 6: Confidence Intervals of Relative Risk Formula

$$CI = \left(\frac{r_1}{r_2}\right) \pm 1.96 * sqrt\left(\left(\frac{1}{a} * \frac{b}{n_1}\right) + \left(\frac{1}{c} * \frac{d}{n_2}\right)\right)$$

Where:

$$r_1 = \frac{a}{a+b} \text{ and } r_2 = \frac{c}{c+d}$$

Table 14: Relative Risk Ratio and Confidence Intervals

Condition or Habit	Relative Risk for Limb Loss	CI 95%
Wrist Pain	2.29	[3.15   1.42]
Phalen Pain	2.29	[2.84   1.73]
Slow Pattern	2.29	[2.99   1.58]
Forearm Pain	2.00	[3.17   <b>0.83</b> ]
Long Press	1.9	[2.69   1.12]
High Forces	1.83	[3.35   1.22]
Thumb Pain	1.83	[2.80   <b>0.86</b> ]
One-Handed Bias	1.78	[2.21   1.35]
Finklestein Pain	1.71	[2.29   1.14]

The first thing to note from Table 14 is that the relative risk of selected conditions or texting habits are all above 1 and therefore at a cursory glance all these variables have a higher relative risk for Limb Loss than the Control group, as expected. However, two relative risk ratios were below one for the lower bounds of a 95% Confidence, they are thumb pain and forearm pain. This is expected as the links for Limb Loss with thumb and forearm pain were weaker than other pain measured variables such as wrist pain and RSI test pains. Conditions and habits that have lower bounds confidence intervals of one or lower should be interpreted with caution as it is uncertain how results would change with an increased population. The two conditions where this occurred (thumb and forearm pain), corresponded with the finding that while wrist pain showed significant difference for the Limb Loss and Control group, the thumb and forearm did not.

Attributable risk is similar to relative risk however instead of measuring how strongly a condition or habit affects a population, it shows how much excess risk there is in a population concerning a condition. The calculation is a percentage-based

measurement where higher percentages indicate a population is more susceptible to the specific condition or habit being analyzed. The formulas (see Equations 7 and 8) to calculate attributable risk are as follows, again with respect to the variables named in Figure 53.

Equation 7: Attributable Risk Formula

$$\text{Attributable Risk (AR)} = p_1 - p_2$$

Where:

$$p_1 = \frac{a}{a + b}$$

$$p_2 = \frac{c}{c + d}$$

Equation 8: Confidence Intervals of Attributable Risk

$$CI = AR \pm 1.96 * \text{sqrt} \left( p * q \left( \frac{1}{n_1} + \frac{1}{n_2} \right) \right)$$

Where:

$$p = p_1 / (p_1 + p_2)$$

and:

$$q = 1 - p$$

Table 15 (similar to the relative risk table) indicates the attributable risk to each condition or habit. As expected, the attributable risk levels of these conditions and habits are significant, however some lower bounds confidence measures are very low, specifically, thumb pain and forearm pain as were seen in the relative risk assessment.

These two conditions were also the lowest attributable risk percentages. Note that some upper and lower bounds are the same as the attributable risk values. This occurs when all participants of the Limb Loss group possess the habit or condition being analyzed.

Table 15: Attributable Risk

<b>Condition or Habit</b>	<b>Attributable Risk %</b>	<b>CI 95%</b>
Phalen Pain	56	[56   56]
Slow Pattern	48	[71   26]
One-Handed Bias	44	[44   44]
Wrist Pain	40	[60   21]
Finklestein Pain	36	[48   24]
Long Press	34	[50   18]
High Forces	32	[51   14]
Thumb Pain	26	[50   2]
Forearm Pain	25	[46   4]

### 4.5.3 Consolidated Risk Assessment

Since this study had a small population size it is an interesting opportunity to analyze each individual's relative risk ratios and sum the total relative risk of individual participants as well as other groups of interest (Limb Loss, sex, hand size) to be compared. Hand size comparison was done by hand surface area with hand breadth across the metacarpal multiplied by palm length; groups were separated by above and below the average hand surface area. Table 16 sums and averages the total risk values for the factors that were assessed.

Table 16: Total Relative Risk

<b>Groups</b>	<b>Total Relative Risk Mean</b>	<b>St. Dev</b>	<b>P-value</b>
Limb Loss	13.37	3.34	< 0.001
Control	6.62	3.84	
Female	10.39	4.63	0.069
Male	7.35	4.71	
Small Hand Area	9.64	4.61	0.164
Large Hand Area	7.62	5.04	

The relative risk of the selected habits and conditions were found to be much higher in the Limb Loss group, averaging scores of 13.37 and 6.62 ( $P < 0.01$ ). Sex was not quite significant enough of a factor for relative risk. Females scored 10.39 and males scored 7.35 ( $P = 0.069$ ). When comparing large and small hand size groups, small hands had a higher relative risk total of 9.64 compared to the large hands who had 7.62 but was not a significant difference with the current population size ( $P = 0.164$ ). All 7 of the Limb Loss group had a Total Relative Risk Factor of at least 9. The sex and hand size comparisons are linked due to males having a larger hand size average.

## **5. Conclusion**

### **5.1 Study Overview**

It is rare to have access to data of this kind and difficult to organize its collection, especially with a population which includes unilateral upper limb amputees. The strength of this project lies in there being a lot of information available due to the inclusion of motion capture, EMG, forces, and survey data. Many variables were analyzed, and each variable was analyzed by separation into a multitude of groups such

as phone size, limb status, sex, texting frequency and more. Even more support is given by the fact that each participant did a minimum of 7 trials each for each phone type.

The study has some weaknesses that should be addressed in the future. Firstly, the population size of 23 makes it difficult to add confidence to the analysis. Regression fitting was a large part of the analysis and is heavily dependant on population size. It would be difficult to add more to the Limb Loss group when considering the rarity of the condition, however a few more participants would bolster group comparisons significantly. The same should be applied to the control group as often there were regressions showing a clear pattern. However, sometimes outliers were needed to be removed which can be difficult to justify in an already small population.

Instrumentation dependability can prove to be a difficult when managing three types of data recording devices at once (Motion Capture, Force Sensors, and EMG). It would be recommended to limit the motion capture reflective markers to the phone, hand, and forearm as the others did not return any useful results and were often covered during trials, leaving gaps in tracking marker data. EMG collection should be expanded to collect not only abduction but also adduction, extension, and flexion. The force sensors used had good resolution however multiple participants exceeded the maximum threshold of the sensor's capability, leaving force curves cut off at the top.

Inconsistent data collection has been an issue in the study. Often times there would be gaps due to instrumentation errors such as missing motion markers, EMG signals too noisy to process, force sensors being left out of pattern trials, and naming errors of the variables. This made large scale calculations difficult to loop while using statistical and computational software.

## **5.2 Future Work**

Social media platforms are typically oriented to have a scrolling interface for users. On a mobile phone this uses the repetitive swiping motion up and down on the phone surface screen. An experiment should be done in the future that begins with the most popular social media platform interfaces and collecting data using a small pressure sensitive force reader.

More EMG information regarding texting should be sought out. By adding more EMG muscle sites to extrinsic muscles there is the potential to assess more than just the abduction motion seen in the current study. Flexion and extension muscle activation readings would help to better understand where muscle activation takes place approaching, during, and after thumb contact. Adduction muscle readings would aid in the analysis of far vs close side force sensors in the same way abduction EMG was used in the current study. Timing between EMG peaks is also of interest to see how it relates to the existing force sensor timing.

Repositioning the smart phone display to a centralized position (reducing the distance between the central and perimeter keys) could show if larger phones become more stable without needing the act of thumb reaching (especially concerning far side keys) while texting.

## **5.3 Recap of Findings**

A recap of this research's findings has been compiled into short form paragraphs as follows: pain and posture (including phone control), thumb forces and EMG response, texting efficiency, anthropometric factors, and risk assessment.

With the present information it is clear that the Limb Loss group has pre-existing hand, wrist, and forearm pain making them a higher risk for RSIs. When analyzing wrist flexion and extension it was found that the Limb Loss group extended their wrists 14 degrees further than the control group while texting ( $P < 0.05$ ). Recall the wrist was commonly reported to have pain in both groups but more significantly in the Limb Loss group. More variability was seen on the X and Z axis than the Y axis, meaning that the phone as a solid body did not move much towards or away from the participants body but would move side to side or up and down. This corroborates the phone rolling along the X-axis (side to side) and pitching in the Z (up and down).

Overall, higher forces were seen in the Limb Loss group with significant differences in force between the groups at Force Sensors B and E of the iPhone, and B of the Samsung. No significant difference was found in the largest phone (Note) even at Force Sensor C where the Limb Loss group averaged 3.12 N higher than the control group. Muscle activation was significantly higher on the largest phone when compared to the medium phone ( $P < 0.01$ ) averaging 0.65 mv higher. The peaks of the small and medium phone were also found to be significantly different with the small phone mean EMG being 0.35 mv lower ( $P < 0.05$ ). The increase in pattern completion time for the smallest to largest phone were 0.94, 2.08, and 2.67 seconds respectively. As the phone's size increased one-handed texting time increased, while two-handed texting completion time stayed the same.

When texting two-handed the control group improved their texting efficiency on each phone type (iPhone, Samsung, Note,  $P < 0.01$ ). High force texters took longer to complete patterns than those with average forces smaller than 6 Newtons. Both sets of

regression curves clearly showed that as keystroke duration increased so did forces. R-sq values of the control group range from 52.1% to 67.4% while the Limb Loss regression ranged from 50.0% to 93.3%. For this population size these should be regarded as strong regressions.

When overlaying individual force sensor data, it is apparent on all phones that forces decreased with increased hand measurements of any kind (i.e. thumb hand widths and lengths). The strongest regression was found on the Note phone and could be related to larger phones being more stable in bigger hands. Pattern completion time may be influenced by hand size, but a larger population study would be needed for concrete evidence. Force variation and force applied to the sensors were directly related. Participants with higher forces saw more variation in forces and were perhaps related to instability of the phone

The relative risk of the selected habits and conditions were found to be much higher in the Limb Loss group than the control group averaging scores of 13.37 and 6.62 respectively ( $P < 0.001$ ).

Revisiting the hypotheses from the end of the introduction.

1. Non-neutral posture is related to localized pain in the hand, arm, and neck.

The Limb Loss group reported high wrist pain and saw wrist angle extensions significantly higher than the control group. Elbow pain was significantly higher for the Limb Loss group as well, however there was no difference in elbow angles; this was due to positioning of the elbow during the experiment protocol. There was neck pain present in both Limb Loss and control groups; necks were tilted in a forward position so that

they may see the phones which were positioned near their laps. The hypothesis was partially confirmed.

2. Texting mechanics and body posture are influenced by phone size.

The largest phone (the Note) posed constant issues for participant's texting mechanics. Larger phone's increased pattern completion times, muscle activation increased, the stability of the phone decreased, and the far side force sensors were difficult to reach. The hypothesis was confirmed.

3. Texting mechanics and efficiency are influenced by anthropometrics and texting habits.

Bigger hands had lower forces, marginally faster pattern completion times on all phones, and could reach far side force sensors better in some cases. The hypothesis was confirmed.

## **5.4 Recommendations**

Some recommendations can be made based on the completed analysis. Mobile phone users should use devices that comfortably fit their hand size. This may prove more difficult as cellphone manufacturers appear to be making larger screen displays as video streaming apps are becoming the new norm for media entertainment. Regardless of phone size, texters should try to text with two-hands as this would share the load between both, decreasing the time required to text and improve stability to help counteract the risk of developing of RSIs of the thumb and wrist.

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## Appendix A – Gustafsson Survey

Details of the Gustafsson survey (2010) that indicates a link between pain and increased mobile phone use. Updated most recently as (Gustafsson et al., 2017)

<b>Baseline</b>			<b>Five-year follow-up</b>					
<b>Baseline Men</b>			<b>Women</b>		<b>Men</b>		<b>Women</b>	
<b>N = 2759</b>			<b>N = 4333</b>		<b>N = 991</b>		<b>N = 1733</b>	
	<b>n</b>	<b>%</b>	<b>n</b>	<b>%</b>	<b>n</b>	<b>%</b>	<b>n</b>	<b>%</b>
<i>SMS</i>								
<b>0 per day</b>	<b>228</b>	<b>8</b>	<b>116</b>	<b>3</b>	<b>47</b>	<b>5</b>	<b>17</b>	<b>1</b>
<b>1–5 per day</b>	<b>1640</b>	<b>59</b>	<b>2508</b>	<b>58</b>	<b>551</b>	<b>56</b>	<b>844</b>	<b>49</b>
<b>6–10 per day</b>	<b>532</b>	<b>19</b>	<b>1031</b>	<b>24</b>	<b>241</b>	<b>24</b>	<b>525</b>	<b>30</b>
<b>11–20 per day</b>	<b>217</b>	<b>8</b>	<b>437</b>	<b>10</b>	<b>99</b>	<b>10</b>	<b>227</b>	<b>13</b>
<b>&gt;20 per day</b>	<b>142</b>	<b>5</b>	<b>241</b>	<b>6</b>	<b>53</b>	<b>5</b>	<b>120</b>	<b>7</b>
<i>Neck/UB pain</i>								
<b>No or missing</b>	<b>2108</b>	<b>76</b>	<b>2323</b>	<b>54</b>	<b>695</b>	<b>70</b>	<b>865</b>	<b>50</b>
<b>Yes, &lt;1 week</b>	<b>277</b>	<b>10</b>	<b>673</b>	<b>16</b>	<b>107</b>	<b>11</b>	<b>232</b>	<b>13</b>

**Yes, 1-3 months** 94 3 340 8 54 5 153 9

**Yes, 1-3 months** 59 2 221 5 31 3 100 6

**Yes, >3 months** 221 8 776 18 104 10 383 22

*Shoulder/UE pain*

**No or missing** 2159 78 3035 70 748 75 1185 68

**Yes, <1 week** 251 9 448 10 86 9 140 8

**Yes, 1-3 months** 124 4 210 5 44 4 95 5

**Yes, 1-3 months** 59 2 148 3 35 4 85 5

**Yes, >3 months** 166 6 492 11 78 8 228 13

*Hand/finger numbness*

**No or missing** 2546 92 3845 89 891 90 1464 84

<b>Yes, &lt;1 week</b>	<b>94</b>	<b>3</b>	<b>198</b>	<b>5</b>	<b>38</b>	<b>4</b>	<b>71</b>	<b>4</b>
<b>Yes, 1 week-1 month</b>	<b>30</b>	<b>1</b>	<b>65</b>	<b>2</b>	<b>19</b>	<b>2</b>	<b>47</b>	<b>3</b>
<b>Yes, 1-3 months</b>	<b>23</b>	<b>1</b>	<b>60</b>	<b>1</b>	<b>15</b>	<b>2</b>	<b>33</b>	<b>2</b>
<b>Yes, &gt;3 months</b>	<b>66</b>	<b>2</b>	<b>165</b>	<b>4</b>	<b>28</b>	<b>3</b>	<b>118</b>	<b>7</b>

## Appendix B – Bernier Survey

Survey Questionnaires Designed by Bernier (Bernier, 2018)

SURVEY A	CONFIDENTIAL	PARTICIPANT: _____
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### 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			
<b>1.1 Gender</b>	<b>1.2 Age</b>	<b>1.3 Height</b>	<b>1.4 Weight</b>
<b>1.5 Please indicate the number of years you have owned a cell phone with text messaging features?</b>			
<b>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.</b>			
<input type="checkbox"/> Light texter (0 – 50 per day) <input type="checkbox"/> Light – Medium texter (50 – 100 per day) <input type="checkbox"/> Medium – Heavy texter (100 – 150 per day) <input type="checkbox"/> Heavy (150 +)	Average number of SMS text messages sent on your mobile phone per day, if available: <input style="width: 100px;" type="text"/>		
<b>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.</b>			
<input type="checkbox"/> Light texter (0 – 50 per day) <input type="checkbox"/> Light – Medium texter (50 – 100 per day) <input type="checkbox"/> Medium – Heavy texter (100 – 150 per day) <input type="checkbox"/> Heavy (150 +)	Average number of non SMS text messages sent on your mobile phone per day, if available: <input style="width: 100px;" type="text"/>		
<b>1.8 What model and type of mobile phone do you use currently?</b>			
<b>1.9 Please indicate your side of limb loss.</b>			
<input type="checkbox"/> Right <input type="checkbox"/> Left			
<b>1.10 Please select only one type of limb loss:</b>			
<input type="checkbox"/> Congenital - Limb deficiency at birth <input type="checkbox"/> Traumatic - Limb deficiency at the time of an accident or event <input type="checkbox"/> Medical - Limb deficiency after birth, possibly from disease			
<b>1.11 Please indicate the year when you had your amputation. (If congenital, please enter year of birth)</b>			
<input style="width: 100px;" type="text"/>			
<b>1.12 Please indicate your dominant side prior to amputation. (If congenital, do not answer)</b>			
<input type="checkbox"/> Right <input type="checkbox"/> 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

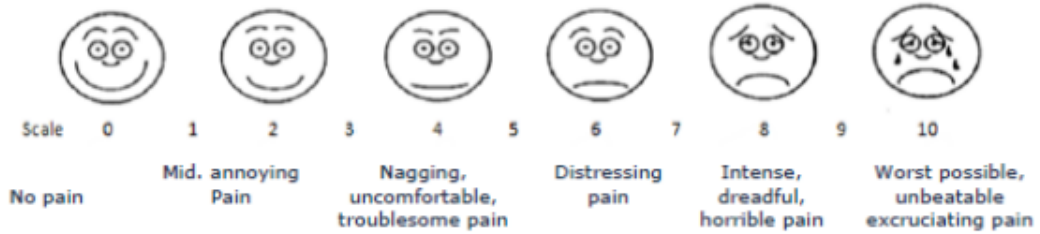
If employed please indicate your job title in the box below:

**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:



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											



**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			
<b>1.1 Gender</b>	<b>1.2 Age</b>	<b>1.3 Height</b>	<b>1.4 Weight</b>
<b>1.5 Please indicate the number of years you have owned a cell phone with text messaging features?</b>			
<b>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.</b>			
<input type="checkbox"/> Light texter (0 – 50 per day) <input type="checkbox"/> Light – Medium texter (50 – 100 per day) <input type="checkbox"/> Medium – Heavy texter (100 – 150 per day) <input type="checkbox"/> Heavy (150 +)		Average number of SMS text messages sent on your mobile phone per day, if available: <input style="width: 100px;" type="text"/>	
<b>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.</b>			
<input type="checkbox"/> Light texter (0 – 50 per day) <input type="checkbox"/> Light – Medium texter (50 – 100 per day) <input type="checkbox"/> Medium – Heavy texter (100 – 150 per day) <input type="checkbox"/> Heavy (150 +)		Average number of non SMS text messages sent on your mobile per day, if available: <input style="width: 100px;" type="text"/>	
<b>1.8 What model and type of mobile phone do you use currently?</b>			
<b>1.9 Please indicate your handedness.</b>			
<input type="checkbox"/> Right <input type="checkbox"/> Left			
<b>1.10 On average, what percentage of all messages sent do you complete one handed.</b>			
<input type="checkbox"/> 0 – 25 %    (I mostly text two handed, where I use both hands for mobile phone support and/or typing) <input type="checkbox"/> 25 – 50 %    (I text one handed occasionally) <input type="checkbox"/> 50 – 75 %    (I text one handed often) <input type="checkbox"/> 75 – 100%    (I text one handed very often)			
<b>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?</b>			
<input type="checkbox"/> 0 – 25 %    (I mostly text one handed using my non-dominant hand) <input type="checkbox"/> 25 – 50 %    (I occasionally use my dominant hand to text one handed) <input type="checkbox"/> 50 – 75 %    (I often use my dominant hand to text one handed) <input type="checkbox"/> 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:

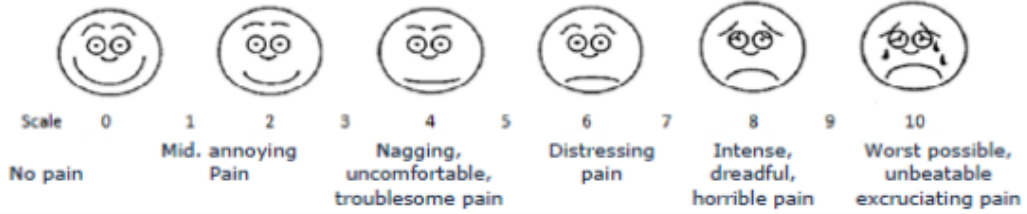
2.3 Please indicate your current job/occupation.

- |   |   |
|---|---|
| <ul style="list-style-type: none"> <li><input type="checkbox"/> Student</li> <li><input type="checkbox"/> Not employed</li> <li><input type="checkbox"/> Employed</li> <li><input type="checkbox"/> Student and employed</li> </ul> | <p>If employed please indicate your job title in the box below:</p> <div style="border: 1px solid black; height: 20px; width: 100%;"></div> |
|---|---|

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 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.**

<b>3.7 Please indicate the time when your pain is the most bothersome (1), second most bothersome (2), and least bothersome (3).</b>		
1. _____ 2. _____ 3. _____	<b>Examples:</b> 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: _____		
<b>3.8 Please indicate the location of your most bothersome (1), second most bothersome (2) and least bothersome (3) pain.</b>		
1. _____ 2. _____ 3. _____	<b>Location of Pain:</b> Thumb Wrist Forearm Elbow	
		Shoulder Neck Back
<b>3.9 Have you ever sought medical care for any of the pain described in this survey?</b>		
<input type="checkbox"/> Yes <input type="checkbox"/> No		
If yes, please explain: _____		

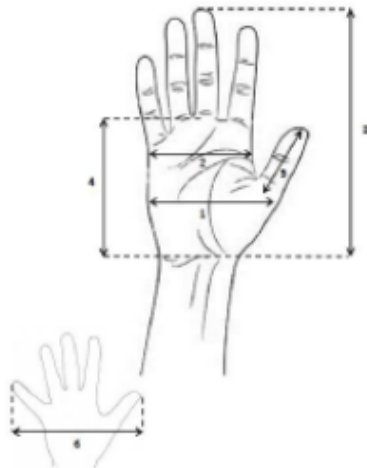
**Repetitive Strain Injury due to One Handed Texting  
Function/Anthropometric Evaluation**

**SECTION A – FUNCTION EVALUATION**

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

Test	Pain	Tingling	Numbness	Comments
Finkelstein	<input type="checkbox"/> Yes <input type="checkbox"/> No	<input type="checkbox"/> Yes <input type="checkbox"/> No	<input type="checkbox"/> Yes <input type="checkbox"/> No	
Phalen	<input type="checkbox"/> Yes <input type="checkbox"/> No	<input type="checkbox"/> Yes <input type="checkbox"/> No	<input type="checkbox"/> Yes <input type="checkbox"/> No	
Dynamometer _____ lb	<input type="checkbox"/> Yes <input type="checkbox"/> No	<input type="checkbox"/> Yes <input type="checkbox"/> No	<input type="checkbox"/> Yes <input type="checkbox"/> No	

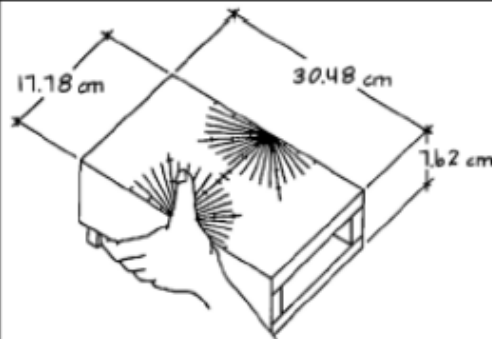
**SECTION B – ANTHROPOMETRIC MEASUREMENTS**



	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 C – Motion Capture Marker Set**

Complete Marker Set for VICON Motion Capture (Bernier, 2018)

1. FRHD – Front Head
2. LTHD – Left Head
3. RTHD – Right Head
4. C7 – 7<sup>th</sup> 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

# Curriculum Vitae

**Candidate's full name:** Ian Douglas Ferguson Lemoine

**Universities attended:**

MScE Mechanical Engineering (2018 – 2021)

*University of New Brunswick*

BASc Mechanical Engineering (2014 – 2018)

*University of New Brunswick*

BASc Geodesy and Geomatics Engineering (2012 – 2013)

*University of New Brunswick*

**Conference Presentations:**

Lemoine I, Biden E, Hill W, “One-Handed Texting and Limb Loss”, *Association of Children's Prosthetics and Orthotics Clinic Annual Meeting*, Portland, Oregon, March 2020. Podium Presentation.