Design of Thumb Keyboards: Performance, Effort and Kinematics

by

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Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Mobile hand-held communication device (smart phone) use is very prevalent and growing rapidly. In addition, there is empirical support for heavy use to be associated with musculoskeletal disorders. This study therefore addressed the physical demand and performance when using these devices. The natural texting style for 20 participants was identified and then participants performed standardized static and dynamic tasks on 4 different types of mobile hand-held devices; a touch screen device and 3 devices with different keyboard sizes and layout; a flip or clamshell design, a PDA style device and a phone with a pull out QWERTY keyboard. Participants rated the effort required to complete each task and for dynamic tasks, keystroke speed was also measured. The time history of angles of the carpometacarpal, metacarpophalangeal and interphalageal joints of the thumb as well as motion of the wrist were determined using small surface makers and an optoelectronic motion capture system. Thumb kinematics were normalized to the maximum range of motion of each joint.

Statistically significant and substantial differences were found for the dynamic condition: The tasks which required the most motion in the flexion/extension axis of the thumb also required the most effort, and that there is an inverse relationship between effort and typing speed, namely that those tasks, or devices which required the highest effort resulted in the lowest typing speeds, and visa-versa. Similarly, results showed that those static tasks which required the most thumb flexion also required the most effort.

Overall, use of the touch screen phone required the least effort for dynamic and static tasks, and also resulted in the highest typing speeds. This could be a result of having the lowest force required to engage the keys. The device which resulted in the lowest typing speed and highest required effort was the flip phone, which also had the highest required force to engage the keys. There was also a weak relationship between user thumb length and required effort, with longer thumb length necessitating a greater about of effort.

Those subjects who used the texting style indentified as the slide style which used forearm rotation with a less flexed thumb reported significantly less effort for all tasks than those who used the claw style which used extreme flexion of the thumb joints. However, texting style had no significant effect on typing speed, indicating that someone could adopt the slide style to reduce muscular effort and potentially the risk of developing musculoskeletal disorders in the upper limbs and neck without sacrificing performance.

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List of Acronyms

3D	3-Dimensional
ANOVA	Analysis of Variance
AP	Adductor Pollicis
APB	Abductor Pollicis Brevis
APL	Abductor Pollicis Longus
CMC	Carpal-Metacarpal Phalangeal Joint
CMCFE	Carpal-Metacarpal Phalangeal Joint Flexion/Extension axis
CMCAA	Carpal-Metacarpal Phalangeal Joint Abduction/Adduction axis
CMCR	Carpal-Metacarpal Phalangeal Joint Rotation axis
DOF	Degrees of Freedom
EMG	Electromyography
EPB	Extensor Pollicis Brevis
EPL	Extensor Pollicis Longus
FPB	Flexor Pollicis Brevis
FPL	Flexor Pollicis Longus
IP	Interphalangeal Joint
IPFE	Interphalangeal Joint Flexion/Extension axis
IPAA	Interphalangeal Joint Abduction/Adduction axis
IPR	Interphalangeal Joint Rotation axis
LVDT	Linear Variable Differential Transformer
MP	Metacarpal-Phalangeal Joint
MPFE	Metacarpal-Phalangeal Joint Flexion/Extension axis
MPAA	Metacarpal-Phalangeal Joint Abduction/Adduction axis
MPR	Metacarpal-Phalangeal Joint Rotation axis
MSD	Musculoskeletal Disorders
OP	Opponens Pollicis
PC	Personal Computer
PDA	Personal Data Assistant
ROM	Range of Motion
RPE	Rating of Perceived Effort
SD	Standard Deviation
SE	Standard Error

ST	Scapho-Trapezial Joint
TM	Trapezo-Metacarpal Joint
WFE	Wrist Joint Flexion/Extension axis
WAA	Wrist Joint Abduction/Adduction axis
WR	Wrist Joint Rotation axis

Design of Thumb Keyboards: Performance, Effort and Kinematics

Chapter 1: Introduction

The use of mobile hand devices in on the rise, and the prevalence of their use is even starting to exceed that of computers, especially among the younger generation in Japan, which has been dubbed the "thumb generation" by the media (Houser and Thorton, 2004). In many cases these students have foregone owning personal computers entirely, using their mobile phones for taking notes in class, browsing the web, and sending emails (Houser and Thorton, 2004). Handheld devices could include cell phones, Personal Data Assistants (PDAs), iPods and gaming devices. The interfaces may include buttons, a stylus, touch screen, thumb pad, or thumb wheel. There has been a lot of talk in the popular press linking increased use of these devices to musculoskeletal disorders. These disorders are known by many terms, some examples are "texting thumb" and "texting tenosynovitis". Like many other repetitive strain disorders, these have been linked to high frequency and long duration of use. However these links are based primarily on case reports of physicians who have encountered patients with chronic thumb pain and who are also frequent text messengers. There is currently no good evidence directly linking excessive use of handheld devices to a debilitating injury of the thumb, due in part to the lack of biomechanical data on the internal stresses of the thumb as it moves through out its 3D workspace or epidemiologic studies. However, there is enough evidence available to raise some concerns about the design of handheld devices, and techniques used by frequent text messengers for text entry, and whether both are optimal for comfort, performance and injury prevention. With the increasing popularity of such handheld devices for communication in both business and personal use, there is a greater need to understand how design and entry techniques can affect comfort, and performance, and shed light on mechanisms for a disabling injury to occur.

The goals of the proposed study are: 1) Observe mobile device use and develop a taxonomy of texting techniques 2) Develop a battery of tests to measure risk factors for thumb musculoskeletal disorders (MSDs), as well as fatigue and performance and 3) Compare between selected texting styles and device types on these measures and 4) Compare values obtained to published benchmarks, where available.

In order to achieve these goals, this study aims to: 1) to determine if individuals will use a wide variety of entry techniques, 2) to determine if technique will have an effect on kinematics, performance and physical effort; performance being measured by typing speed, 3) to determine if task difficulty and performance will change depending on the thumb motion direction and key position, 4) to determine if task difficulty and performance will change depending on device type.

The kinematics collected in this study could be applied to design and injury prevention approaches in the future.

Chapter 2: Review of Literature

2.1 Literature Review:

There have not been many investigations into the kinematics and performance issues of thumb text entry, and those that have, have been largely qualitative and based on medical case studies. However, there have been a few studies on the basic kinematics and operation of the thumb, which have laid the groundwork for more complex and quantitative analysis of thumb motion in manual tasks. There are also numerous studies which investigate performance and comfort issues for full sized keyboards which could provide insight into what quality measures should be used when evaluating keyboard design from a biomechanical perspective.

The need for a more quantitative method of evaluating the kinematics, performance, and effort of thumb text entry stems from the lack of concrete data linking these typing tasks to the repetitive stress injuries that have received so much media attention. One theory is that the use of mobile hand devices places the thumb at its end ranges of motion, both at full extension and full flexion of the thumb, which may place undesirable loading on the musculature and passive tissues. There have been some medical case studies linking the use of handheld devices to De Quervain's disease, an irritation of the tendons at the base of the thumb which results in a swelling of the extensor retinaculum in the first dorsal compartment (Jonnsson et al, 2007) and even an aneurism of the radial artery (Behar et al, 2007). However, it should be noted that De Quervain's disease, which compresses the tendon causing increased tension and reducing the fluidity and range of flexion at the interphalageal (IP) joint, has also been linked to a plethora of other activities, including everything from repetitive use of scissors and sewing needles to bricklaying, so linking it to the use of thumb keyboards alone may prove difficult (Moore, 2003). To date, no study has been performed which quantifies the demands on the soft tissues of the thumb during the use of handheld devices. Therefore there is currently no biomechanical basis for injury prediction and prevention, or even for the assumption that the thumb is not capable of meeting the demands placed on it during the use of thumb keyboards.

A recent study in 2010 by Berolo, Wells, and Amick, provided the first epidemiological evidence of a connection between the higher use of hand held devices and increased musculoskeletal disorders in the upper limb, neck and shoulders. Using cross-sectional design, an internet-based questionnaire was used to collect daily mobile hand-held device use and pain symptoms in the upper extremity and neck in 140 participants. Results were dichotomized in to high and low usage levels, and any or no pain in the upper extremities. 98% of participants reported using a hand-held mobile device, and 84% reported pain in at least one part of the upper extremities. The most common pain sites were at the base of the thumb and at the shoulder and neck. Significant associations were found between amount of internet browsing and pain at the base of the right thumb, and between the total time spend using hand-held devices and pain in the shoulder.

To date, almost all of the work done studying the thumb has been to understand its complex motion, coordination of its joints and force production (Li and Tang, 2007; Baker et al, 2007; Kuo et al, 2002; Pearlman et al, 2004). However, these have focussed on simply describing the kinematics of the thumb, rather than understanding the demand imposed on the thumb to perform particular motions or tasks. In the past, researchers have used many methods to track the motion of the thumb including goniometry and video fluoroscopy. But more recently, passive motion capture with surface markers has made mapping the motion of the thumb much less restrictive than it had been previously which makes a dynamic analysis of thumb kinematics much less problematic.

A study by Valero-Cuevas and colleagues in 2003 attempted to develop an EMG-Muscle force model of the thumb. They collected fine wire EMG from the 8 muscles of the thumb and the first dorsal interosseus, and thumb tip forces in a series of pulp and key pinches. They then developed a model which they found either consistently underestimated thumb tip forces, or misrepresented the thumb tip force vectors. They determined that this was most likely due to the kinematic description of the thumb, and that the commonly accepted five degree of freedom description of thumb kinematics (Kapanji, 2007), may be an oversimplification, and that this definition should be re-evaluated.

There has been some work done on attempting to quantify thumb disability by plotting the workspace of the thumb. A paper published in 2003 devised a method of defining thumb disability by comparing the 3D workspace of the thumb in an injured subject to the 3D workspace of an uninjured subject (Su et al., 2003). A passive motion tracking system was used to track the tip of the thumb relative to a local coordinate system on the wrist. The subjects performed full circumduction of the thumb at full extension, and full flexion of the IP and metacarpal-phalangeal (MP) joints. The remainder of the workspace was modelled by joining the two paths with a series of straight lines, forming an irregular cone. Their theory is that an individual with a thumb injury would draw a smaller volume under these conditions than an uninjured individual. The investigators in this study did not collect any data regarding muscle activity or exertion. It does not give any insight into how a change in 3D workspace can be used to diagnose a specific musculoskeletal disorder or the mechanism of the injury that led to it, only how it can be used as a general indication of thumb impairment. Recently, a paper published by Tang and colleagues in 2008 used passive motion tracking to map the maximal, and operational workspace of the thumb (Tang et al., 2008). The results showed that the angular ranges of motion of the operational workspace were less than 65% of the maximal workspace (Tang et al, 2008). In this study, the thumb was always fully extended, so only the outer shell of the workspace was considered, and the changes in operational workspace with increased flexion of the IP joint was not investigated. No data was collected on the level of discomfort or effort at each angular position through either rating of perceived effort (RPE) or electromyography (EMG). The subjects were only asked to randomly move their thumb around in a space which felt comfortable when determining the operational workspace, and had them move around the active, unassisted limits of circumduction to determine the maximal workspace. From the perspective of design of thumb operated devices, its applications are limited, providing information about only one shell of the total 3D workspace of the thumb. This study however offers a good starting point for the design of more comprehensive studies. This result also seems to confirm the belief by many (but not all) designers that the keys of these handheld devices should be placed as close to one another as possible to maximize comfort (Karlson et al, 2006). This result also serves to draw attention to bad designs which use anthropometrics to define hard physical constraints such as maximum reach, without considering what a comfortable operating range is.

This is also confirmed in a study by Karlson et al (2006) which compared perceived exertion during the use of different styles of handheld devices. They created 3D solid models of a large and small candy bar phone, a flip phone, and a PDA using a rapid prototyping system, and tracked motion of the thumb and the model using an Optotrak system. A grid of circular targets was laid out on each model and the subjects were asked to move rapidly between different targets for 5 seconds. Speed and RPE were used as a means of determining the level of difficulty of the movement. It was found that key size had little effect on ease of use, but a smaller key spacing decreased exertion and increased speed. Another interesting observation of this study in that the direction of motion has a large impact on the level of exertion in thumb motion, even when the motions are along the same line of action. On the right hand for example, moving NW to SE is far more difficult than moving from SE to NW. This difficulty is likely a result of a physical encumbrance, and this is of particular concerns with regards to usability.

With regards to performance issues, Houser and Thorton (2004), that determined the average typing speed of Japanese students on a variety of devices, including handheld devices with a full QWERTY keyboard, touch screen, cell phone, personal computer (PC), and a pencil and paper. 24 Japanese students were asked to perform 2 minute transcription tasks in both English and Japanese. Results showed that, when writing in their native language, their typing speed on a cell phone was very close to their typing speed on a PC, with 16.8 words per minute versus 22.5 words per minute. These were followed by touch screens at about 10 words per minute and thumb keyboards at 7.6 words per minute. Pencil and paper was the fastest at 31.1 words per minute. English values were considerably lower in all categories, partly because of unfamiliarity with the language and grammar which lead to more transcription errors, and partly because of unfamiliarity with the QWERTY keyboard. In Japan most English keyed entry devices have the keys arranged in alphabetical order which they feel is more intuitive. The authors plan to have a future study to allow the students more time to become familiar with the entry devices.

While there have not been many studies aimed at improving the performance of people using thumb keyboards, there has been a considerable amount of work done in this area for full PC keyboards. One such study by Shieh and Lin in 1999 brought together a wide range of work to develop general design principles that could be used to design an ergonomic key arrangement for any language. The main principles were that the highest frequency letters should be placed on the home row, that successive keystrokes on the same digit should be minimized, which means that letters with high word association should be placed on opposite hands, and that high frequency letters should be placed under the index and middle fingers. Some of these principles could be applied to thumb keyboards as well if the biomechanical data is available. For most of these devices, the thumbs are the only digits available, but previous studies have shown that the difficulty and speed of movement is highly directionally dependant (Karlson et al. 2006). Therefore a key arrangement could be developed that places high frequency letters along vectors that require the lowest level of exertion, and that place letters with high association under opposite thumbs.

There have also been many studies expressing the importance of tactile feedback in accuracy, and therefore overall typing speed. This is of particular concern in handheld devices as many of them have touch screens or flat keypads that have no tactile feedback.

A new trend that is being found in an increasing number of handheld devices, both in terms of type and brand, is touch screen controls. This mode of control is popular because of the flexibility of the control interface, which makes it quite simple to combine several different functions into one device, such as Apple's iPhone, which combines a cell phone, web browser, data storage device, media player, and portable gaming device into one compact handheld device. Touch screen devices are also simple to operate, since the user need only use their finger or thumb to interface with the device, rather than a trackball or stylus.

However, despite the benefits of touch screens, it does have its own set of problems with regards to text entry. One problem is the lack of tactile feedback. It has already been established in previous studies, that accuracy, and stability of motion patterns are significantly decreased with tactile feedback is removed, usually accomplished by numbing the fingers in these particular studies (Rabin et al, 2003). Some models of touch screen devices have tried to address this by making touch screens that "click" when a force is applied to them. However, this does not allow the user to feel which particular key they are pressing, so they are still required to look at the keyboard when entering text. Another characteristic of touch screen devices is that a larger key size is required to avoid touching the wrong key, or touching multiple keys at the same time. This isn't an issue with conventional keyboards where the keys are independent, and even if multiple keys are touched, a key press force can still be focussed on a single key. One study suggested that the minimum key size for a touch screen is about 8mm by 8mm, which is significantly larger than the keys on conventional handheld devices (Schedlbauer et al, 2006). This would have significant impact on the biomechanics of thumb typing since the keyboard would have to be larger and therefore the total reach of the thumb greater, in order to complete typing tasks.

A study by Park and Han in 2010 sought to investigate the effect of touch screen button size and location. They used three button sizes, with widths of 4, 7 and 10 mm, and 25 locations on the screen. They had their participants perform a series of single key presses and used first transition time and total completion time as a measure of performance, as well as number of errors and subjective measure of convenience on a scale of 0 to 10. Their results showed that the largest button size result in better performance over all measures. They hypothesized that in lieu of tactile feedback, the user needs to rely more on visual feedback, and that this is reason that larger keys improve response time and reduce errors. They also found that the keys which are easiest to press, and result in the highest performance are those at the end range of extension, while those at the end range of thumb flexion and beyond the end range of extension are the most difficult to press.

2.2 Anatomy of the Thumb

The thumb contains 5 bones, the distal phalange, the proximal phalange, the metacarpal, the trapezium and the scaphoid. These have four joints, the scapho-trapezial (ST) joint, the trapezo-metacarpal joint (TM), which is more commonly known was the carpo-metacarpal joint (CMC), the metacarpo-phalangeal (MP) joint, and the interphalageal (IP) joint (Figure 1).

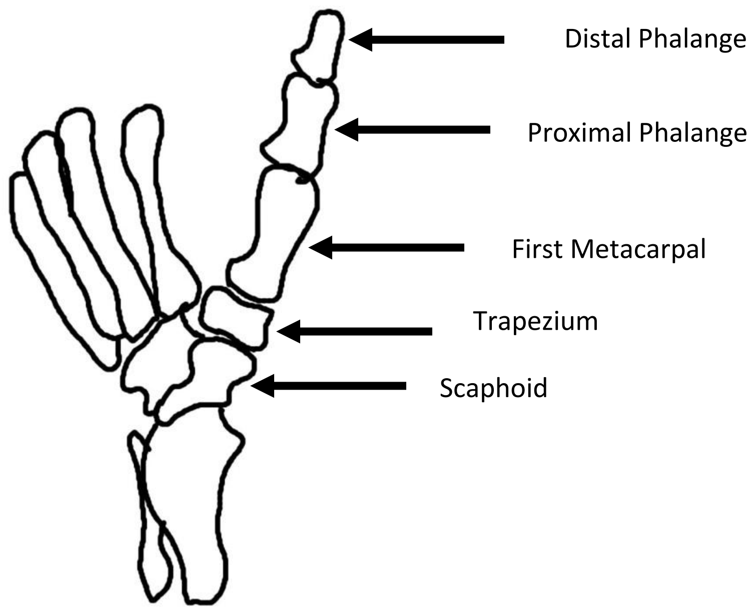
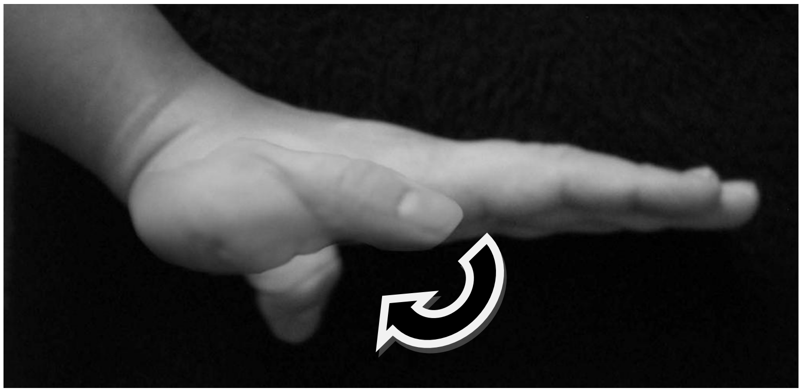


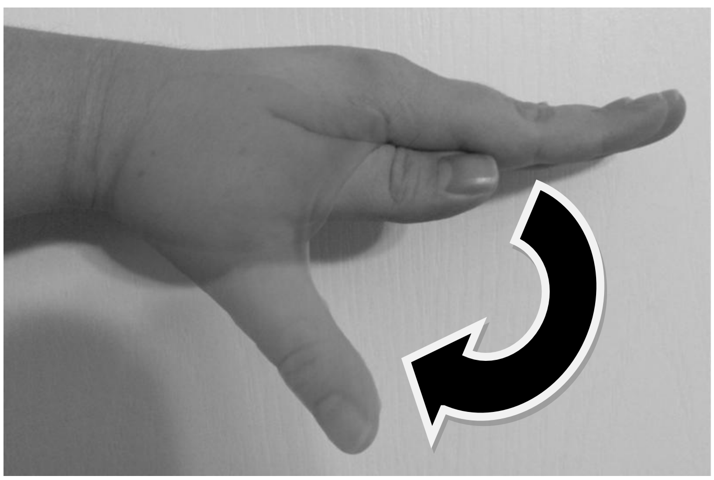
Figure 1: Bones of the Thumb

These bones and joints give the thumb the generally accepted five degrees of freedom necessary for opposition. Although, it should be noted that at study by Valero-Cuevas and colleagues in 2003 suggested that a 5 DOF model which includes IP flexion, MP flexion, and CMC flexion, abduction and rotation, may be oversimplified, and that the basic kinematics of the thumb may need to be re-evaluated. The primary movements of the thumb are flexion/extension, adduction/abduction, and pronation/supination, and some degree of axial rotation.

a)



b)



c)

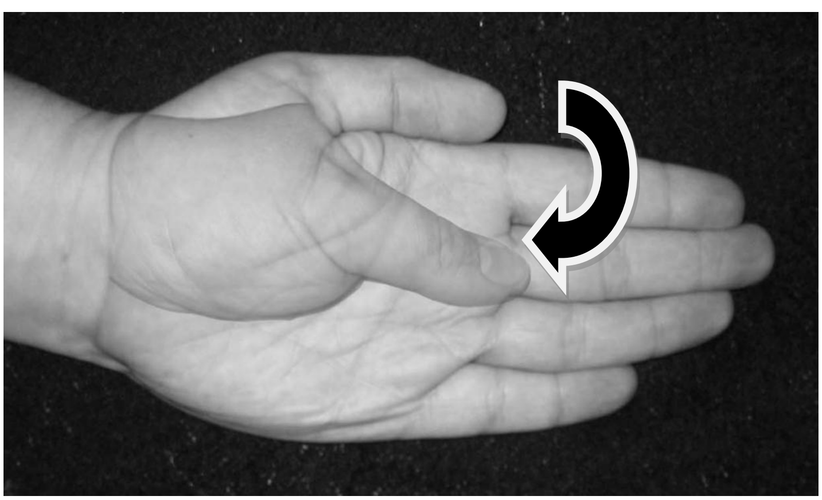


Figure 2: Motion of the thumb a) flexion extension b) adduction abduction c) pronation supination

Much of this mobility is due to the geometry of the CMC joint, which has been described as having the curvature of a saddle on a scoliotic horse, the two joint surface slide against each other along two curved axis allowing the thumb to take position anywhere in space.

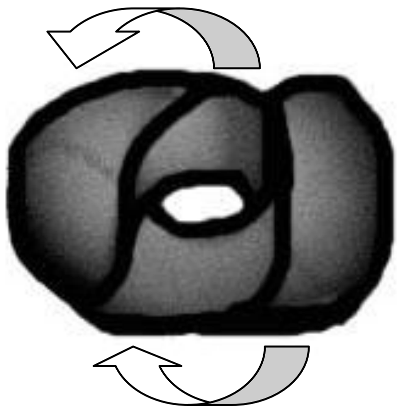


Figure 3: Motion of the CMC Joint

The IP and MP joints a typically described as simple hinge joints, although there is a certain degree of laxity in the joints which allow for some axial rotation.

The 8 muscles responsible for the movement of the thumb are: the abductor pollicis brevis (APB), opponens pollicis (OP), flexor pollicis brevis (FPB), adductor pollicis (AP), flexor pollicis longus (FPL), extensor pollicis longus (EPL), extensor pollicis brevis (EPB), and the abductor pollicis longus (APL).

The APB is an abductor of thumb, and is used primarily for positioning. It is also uniquely able to place the thumb in the “pinch” position while in opposition. The OP is a pronator and opposer of the thumb. The AP is a fan shaped adductor muscle that supplies most of the power in opposition. FPB is a flexor of the MP and CMC joints. APL, and abductor of the thumb, moves thumb the lateral or radial and prevents the collapse of the 1st metacarpal under the adductors. EPB performs the same function as the APL. EPL is an IP extensor, MP and CMC extensor and adductor, and an external rotator of the 1st metacarpal. FPL is an IP flexor. The most important muscles for thumb motion are the EPL, FPL, AP and the APB (Brown, 1988)

The use of fine-wire EMG increases the length and complexity of the study compared to the use of surface electromyography. The use of EMG, especially surface EMG, mayalso influence the motion patterns of users due to the encumbrance of the wires or electrodes, which may have interfered with our ability to accurately determine what effect texting style has on measures of effort and performance. Another issue is that IEMG varies as the muscles lengthen and shorten (Long, 1970), which makes it difficult to accurately relate these values to factors such as motion direction in dynamic tasks such as those performed in this study. Although IEMG is better suited to isometric contractions, the inclusion of EMG may still allow documentation of how muscular demand is distributed to all of the different muscles during the typing tasks and effect of factors such as gender and typing style.

Chapter 3: Methodology

This study focuses on three basic measures: performance, and comfort, and kinematics.

Real devices were used as opposed to mock-ups because of the importance of tactile feedback in the use of handheld device. Studies have shown that the absence of tactile feedback does not have a significant effect on the speed of an individual keystroke. It does have a significant impact on accuracy, and the ability of the subject to hit the intended target, requiring time for correction of the motion path, and the use of muscles that would normally not be used for the intended tasks, which may impact the measure of perceived exertion (Rabin and Gordon, 2003). For the procedures described below, the tasks were repeated for a one handed flip phone and three types of two handed devices shown in figure 4, a PDA style device with a smaller QWERTY keyboard, a candy-bar phone with a larger slide-out QWERTY keyboard, and a touch screen phone. We also identified the texting style used by the subject and grouped it into one of the styles defined in the taxonomy for an analysis of texting style.

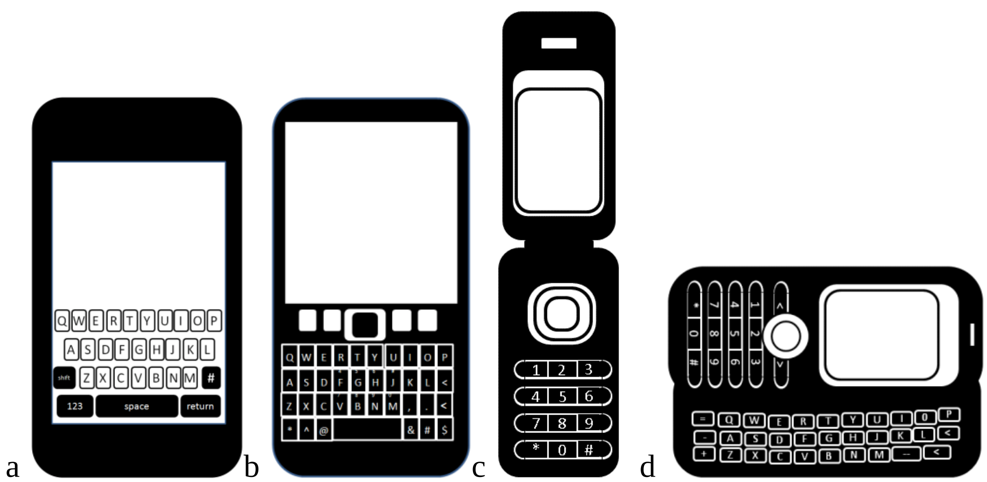


Figure 4: Handheld devices: (a)touch screen (b)PDA (c)Flip Phone (d) Expanded QWERTY

Devices were used two handed except the flip phone which was held in the right hand with the left hand supporting the right hand from underneath, however the number of keys pressed was equalized between devices.

3.1 Participant Selection

There has been some suggestion that younger people tend to use their thumb more for precision tasks while those of an older generation tend to use their index finger (Houser and Thorton, 2004). This may affect the strength, endurance, precision, and degree of motor control of the thumb. Therefore age was controlled for this study. In this case, the demographic of greatest concern is individuals who have grown up in the electronic age, have experience with text messaging, and are frequent users of handheld devices. In other words, university age students. Participants in this study ranged in age from 18 to 30. Subject pool consisted of 9 females and 11 males, 8 of the subjects had the slide style and 12 had the claw style. 5 of the subjects would be considered novice users who don't own handheld devices and don't use them on a regular basis. Subjects who have had any serious upper extremity injuries in the past six months, or who were currently experiencing any chronic pain or stiffness in the

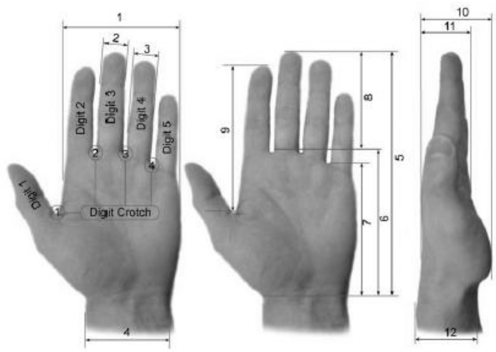


Figure 5: Hand Measurements Dimensions

upper extremities were excluded from the study. We also only wanted participants who have some familiarity with the layout of the QWERTY keyboard, so individuals from countries where this layout is not the norm were excluded as well.

Because there is a wide range of hand sizes both within and between sexes, measurements were taken so that hand size could be accounted for in the statistical model if necessary (Fig 5). The measurements taken were hand length (5), girth (1), and thickness (11), palm length (7), digit 3 length from tip to 3rd MP joint (8), and thumb length from tip to CMC joint. Static range of motion of the thumb joints were also measured using a finger goniometer using the standards published by the American Academy of Orthopaedic Surgeons (1965).

3.2 Developing a Taxonomy of Text Messaging Techniques

It has been noted from personal observation of text messengers, and observation of video footage of text messaging competitions that there are very different techniques employed by the users of handheld devices, and that these techniques have one and two handed variations. It is expected that changing the entry technique would change the biomechanics of text entry and therefore impact the kinematics, level of effort, and performance of the thumb when typing. It was therefore necessary to classify the different techniques, and to address each different technique in the collection protocols of this study. Preliminary observation detected two basic styles.

3.2.1 Claw Grip

This grip (fig 6) is characterized by extreme flexion of the IP joint of the thumb. Side to side motion is accomplished by flexion/extension of the CMC joint and up-down motion across the keyboard is accomplished by adduction/abduction of the thumb at the CMC joint. This grip is often accompanied by flexion of the fingers that support the handheld device. This grip has both a one and two handed variation.

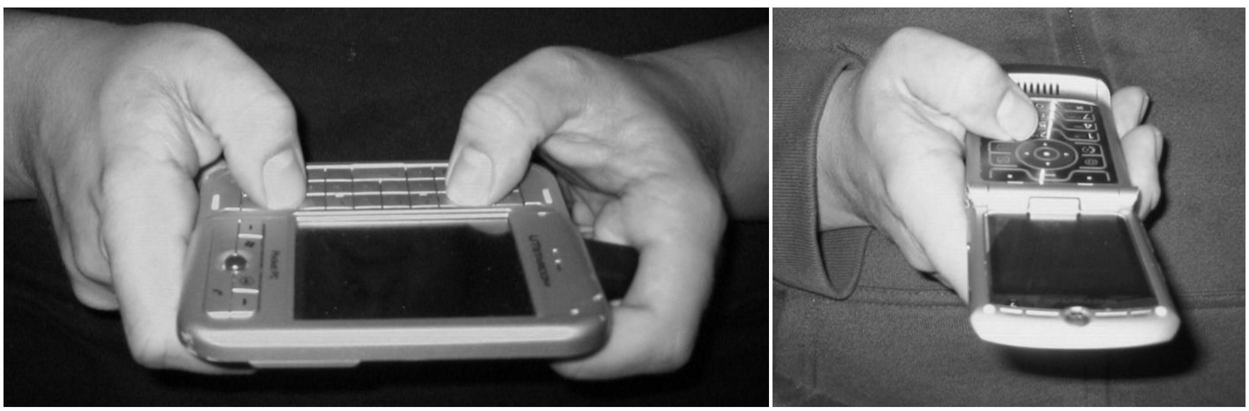


Figure 6: Claw Grip using two, and one handed devices

3.2.2 Slide Grip

This grip (fig 7) is characterized by little or no flexion of the IP joint of the thumb and fingers. Up-down motion is still achieved by adduction/abduction of the thumb at the CMC joint. Side to side motion is now achieved by pronation/supination of the entire forearm, with a minimal amount of movement in the flexion/extension direction at the CMC joint. This grip has both a one and two handed variation. In the one handed variation, the user may roll the phone in the palm of their hand to reach the keys at the extreme inner and outer ranges of motion.

Figure 7: Slide Grip using two and one handed devices

3.2.3 Intermediate Grips

Some participants used styles that were combinations of the two styles described (fig 8). There is a moderate degree of flexion of the IP joint. Up-down motion is achieved by adduction/abduction of the thumb at the CMC joint. Side to side motion is achieved by a combination of pronation/supination of the forearm and flexion of the CMC joint.

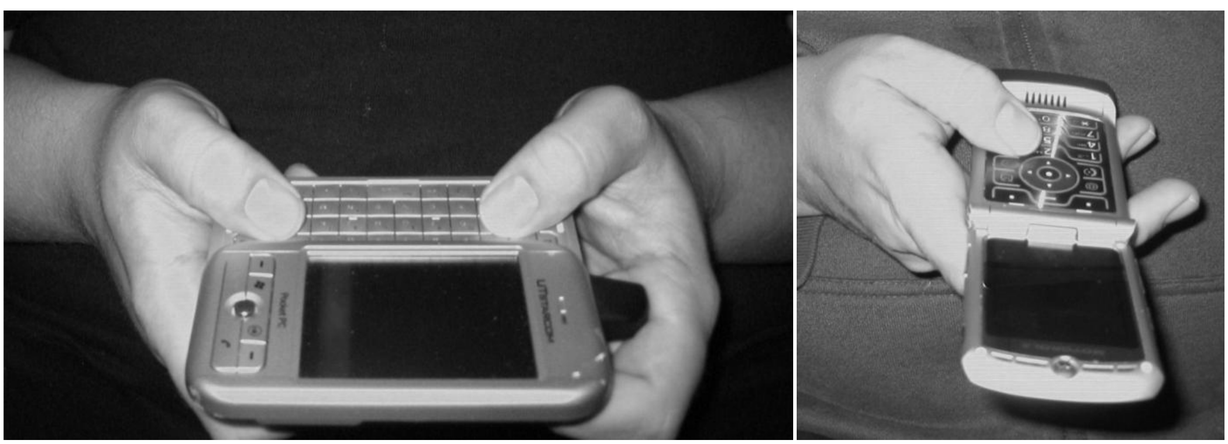


Figure 8: Intermediate using two and one handed devices

3.3 Taxonomy and Speed

Since we want subjects to use their natural texting styles, rather than forcing them to use a specific texting style, a preliminary study with a larger population was performed in order to find a subsample of participants in each taxonomy category for a more detailed kinematic analysis. Prior to participation, participants were asked to fill out a short survey adapted from Berolo, Wells and Amick

2010, included in Appendix A, which asks them questions about their usage habits, so that they could classified as either frequent or casual users. Participants were all asked to transcribe the following sample of text.

> *"The foxy lady quietly slipped out of the ziggurat and rode the purple bus to the zoo. She fed the elephant a deadly peanut before the kangaroo knocked her quickly on the head and jumped away. She was very lucky to receive an xray before the sassy walrus whacked her with a smoked jellyfish"*

The text was chosen to provide a balanced mix of typing conditions, including switching between hands for successive keystrokes, using the same hand for successive keystrokes, and multiple taps of the same key. It also uses every letter in the English alphabet at least twice, and only contains words that should be simple to spell, for example the participant won't have to pause for a moment to remember if the "I" or the "e" comes first. They repeated the transcription on each of the four devices, while their hands were recorded with a video camera. Two independent observers used this video to classify each participant into one of the taxonomy categories using the criteria outlined in the taxonomy. Both observers have had training in biomechanics and observation of joint motion, and have formal knowledge of human anatomy. The assignment of texting style was primarily based upon the level of thumb flexion and pronation/supination of the forearms during typing. From these trials, 10 subjects from each of the claw grip and slide grip taxonomy categories were contacted and brought back in to the lab for a more detailed kinematic analysis using passive motion tracking. Subjects whose styles clearly fell into one or the other styles were recalled for further testing.

An accelerometer was mounted on the entry device to record the keystrokes, allowing us to measure changes in keystroke speed in response to the protocol and time. The Brüel and Kjær 50 g uniaxial accelerometer was conditioned by an ENTRAN BS30A amplifier and 1000 Hz low pass filter and recorded at 2048 Hz.

3.4 Key-press Force

Since it could have an effect on required effort, the keypress force was measured for each device by using a ¼ inch diameter flat ended probe instrumented to measure axial load (Schaevitz LVDT with a Daytronic 3230 LVDT Conditioner). The probe was centred over device key and force gradually increased using the index finger. The keypress force was determined as the maximum force recorded before the button clicked. There was no keypress force recorded for the touch screen as it operates on capacitance rather force. However, some users may press harder than necessary when using the touch screen if they are having trouble engaging the keys because of a film of dirt and oil interfering with the connection between the screen and the thumb however there is really no reliable way of determining what would be the standard force under these conditions since there is no clearly defined force cutoff that will result in the engagement of the key. So for the purpose of this study, the screen was kept clean, and it was assumed that the phone was used properly and that zero force was required.

3.5 Kinematics and RPE

3.5.1 Equipment and Processing

For the second part of the study with a sub group of participants, kinematics were collected at a frequency of 60 Hz using a Vicon passive motion tracking system with 7 MX20+ cameras and the Vicon v1.4 software.

4mm diameter retro-reflective markers were fixed to the dorsal surface of the thumb at the IP joint, MP Joint, CMC joint and thumb tip using colostomy paste (Fig 9). Three markers were placed on a "T" frame fixed to the dorsal surface of the thumb at the centre of the distal and proximal phalanges and 1st metacarpal in order to determine the 3D rotation of the thumb a previous study has shown that there is good agreement between surface markers and bony processes and that skin shift is minimal (Kuo et al, 2002; Kuo et al, 2003). Markers were also placed on the dorsal surface of the hand at the 2nd and 4th MP joints, at the wrist on the radial and ulnar epicondyles and on the elbow. The four markers on the hand and wrist and the CMC marker formed a reference system to determine flexion/extension, and adduction/abduction of the thumb. Markers on the wrist and on the elbow determined forearm pronation and supination.

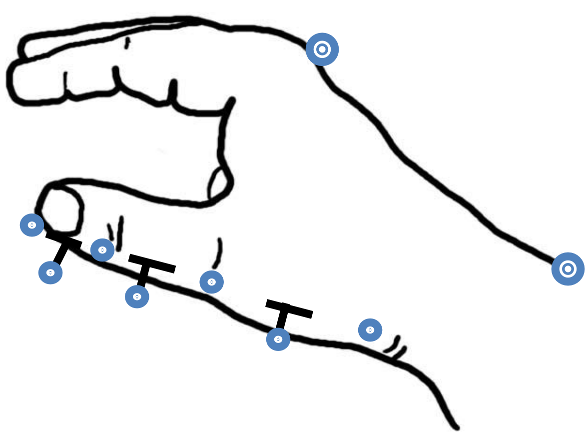


Figure 9: Marker placement

In order to calibrate the model template every participant holds a static calibration posture for a few seconds and this trial is applied to the model. For the calibration posture, the participant would hold the device in their right hand, with the dorsal surface of their hand and forearm facing the camera.

Missing markers were replaced using the pattern fill function included in the Vicon software. The location of a missing marker was defined by the location of the next most distal marker on the same segment.

An Eulerian X-Y'-Z" convention was used to define thumb orientation in 3D space (Zatsiorsky, 1998) flexion and extension is be about the X axis, pronation and supination is about the Y axis, and adduction and abduction is about the Z axis. The zero angle for flexion/extension is defined as if the thumb is laid flat on the table, palm down. The zero angle for abduction/adduction is where the thumb is fully adducted. The zero angle for rotation is where the thumb is flat, palm down, on the table.

The raw time history of joint angles was filtered at 6 Hz using a 2nd order dual pass butterworth filter, with 10 points of padding at either end of trial using the first and last values of actual data. After this was completed, there were still peaks which appeared to be the result of missing or mislabelled markers. At these points, the angular velocity was calculated, and was found to be on the order of 180000 deg/s, far beyond what is physically possible, normally on the order of 75 deg/sec (Janke, 2004) so these points were removed from the trial and replaced by a linear interpolation between the points.

Collected kinematics allowed us to determine keystroke speed, and its dependence on the thumb motion vector, and the direction along that vector. It also allowed us to quantify the motion patterns adopted by the participant when typing on the different devices. RPE was collected as a measure of task difficulty. Subjects were instructed rate their discomfort on a 0 – 10 visual analog scale, with 0 representing no discomfort at all, and 10 representing extreme, almost unbearable discomfort. Their rating was recorded using an electronic slide that recorded up to 3 decimal places.

Previous studies have fixed the hand to an anchored brace and determined thumb joint position relative to a coordinate system on the brace. Although this does make motion analysis less complex, there was a concern that bracing the hand would force the subject to use unnatural motion patterns, because certain movements are constrained, or because the brace performs stabilization that would otherwise have to be performed by a muscle. Since we are not restraining the hand, three markers were also placed on the bottom surface of the entry devices in an equilateral triangular arrangement to track their movement relative to the hand.

3.5.2 Calculation of Kinematic Summary Variables

In order to describe the motion patterns used by each subject as they performed various kinematic tasks, several variables were calculated to summarize the time history of each joint angle during each trial. All calculations were performed after the processing described above.

The first variable was the mean value for the time history of the joints angle over the course of the kinematic trial. The second variable was the total angular range of motion achieved by the joint over the course of the kinematic trial. This was calculated by subtracting the smallest angle in the time series from the highest angle in the time series.

The next variables calculated were the 95^{th} and 5^{th} percentile of the total angular range of motion for a given trial. This was calculated by arranging the angular values from smallest to largest, and picking out the values that fall on the 95^{th} and 5^{th} percentile of the distribution. These values were used instead of the absolute maximum and minimum in order to avoid including any abnormally high or low values in angular motion, resulting from motion or processing artefact that was not accounted for in the processing.

Finally the time normalized path length was calculated for each joint axis of rotation. This was calculated by calculating the absolute length of a line drawn (in degrees) between each successive point in the time series, adding up all of these values for the entire time history, and then dividing this sum by the total time taken to complete the trial. This value was calculated to describe how much motion there was in a given joint axis of rotation during a kinematic trial.

3.6 Operational Workspace

In order to compare maximal thumb range of motion to the operational workspace during device use, each participant performed a complete circumduction of the CMC joint, with IP and MP joints fully extended as kinematics are collected. Two of these trials were collected. Participants also performed a maximal flexion of the entire thumb; by bring the tip of their thumb as close to the CMC joint as possible. Two trials were also collected for this.

3.7 Quantification of Motion Patterns

The participants moved their thumbs back and forth between target keys along different vectors, and distances from the thumb. Each trial consisted of a sequence of keystrokes shown in Table 1 that cover the operational workspace for the device, and two repetitions of this trial was performed for each device while kinematics are collecting using the Vicon motion capture system. This allowed us to quantify the motion patterns under standardized conditions.

Vector	Flip Phone	Expanded QWERTY	PDA	Touch Screen
V1	3#3#	p↵ p↵	p Ctrl p Ctrl	p↵ p↵
D1	1#1#	y↵ y↵	y Ctrl y Ctrl	y↵ y↵
H1	*#*#	n↵ n↵	Space Ctrl Space Ctrl	Space↵ Space↵
H2	3131	pypy	pypy	pypy
V2	*1*1	nyny	Space y Space y	Space y Space y
D2	3*3*	pnpn	p Space p Space	p Space p Space

Table 1: Targets for static and dynamic tasks

To measure performance, subjects were asked to move the thumb rapidly back and forth between two target keys on a cell phone or PDA for a set amount of time. Three sets of targets set along radial vectors at three angles of thumb abduction, between maximum outer reach and maximum inner reach of the thumb was chosen in order to determine the spatial and directional dependence of task difficulty, kinematics and performance. Each subject performed 2 repetitions of each condition, rapidly moving their thumb tip between the two targets as quickly as they could for 10 seconds. The order of the conditions was completely randomized. If the designated keys were not depressed, the trial was discarded and the participant repeated the trial.

Vector	Flip Phone	Expanded QWERTY	PDA	Touch Screen
H	* #	n ↵	Space Ctrl	Space↵
V	3 #	y ↵	y Ctrl	y↵
D	1 #	p ↵	p Ctrl	p↵

Table 2: Buttons pressed for each motion vector

Button	**Flip Phone**	**Expanded QWERTY**	**PDA**	**Touch Screen**
1	1	p	p	p
2	3	y	y	y
3	*	n	Space	Space
4	#	↵	Ctrl	↵

Table 3: Buttons pressed in static holds

In addition to dynamic tasks, the difficulty of performing a given key press was determined for a static hold. Subjects were asked to hold down a key for 20 seconds, and then rate the difficulty of the task. Again, targets were chosen along radial vectors at three angles of thumb abduction, and at extreme outer, extreme inner, and mid range of reach. Order of conditions was fully randomized and subjects performed 3 repetitions of each condition. Previous studies have suggested that the point of greatest strain should occur at extreme abduction and flexion (Jonsson et al, 2007).

3.8 Statistics

All analysis was performed with SPSS statistical software version 13.0, with the exception of post-hoc tests which were performed using JMP statistical software version 8.0.

3.8.1 Taxonomy and Speed:

The trial conditions of thumb motion vector, and device type were fully randomized and subjects used their natural texting style. A repeated measures general linear model analysis was performed using motion vector and device type as within-subject factors and texting style as a between subject factor to determine which main and interaction effects influenced typing speed. The model was calculated with an alpha of 0.05. Post hoc Tukey interval tests were performed to determine if there is a significant difference between the device types and motion vectors. A linear regression was performed to determine any relationship between thumb length and typing speed. A one-way general linear model analysis was performed in order to determine any gender effects. The model was calculated with an alpha of 0.05.

3.8.2 Kinematics and RPE: Dynamic

The trial conditions of thumb motion vector, and device type were fully randomized and subjects used their natural texting style. A repeated measures general linear model analysis was performed using motion vector and device type as within-subject factors and texting style as a between subject factor to determine which main and interaction effects influenced RPE. The model was calculated with an alpha of 0.05. Post-hoc Tukey interval tests were performed to determine if there is a significant difference between the different device types, and the different texting styles, with regards RPE. A linear regression was performed to determine any relationship between thumb length and typing speed. A one-way general linear model analysis was performed in order to determine any gender effects. The model was calculated with an alpha of 0.05.

3.8.3 Kinematics and RPE: Static

The trial conditions of thumb motion vector, and device type were fully randomized and subjects used their natural texting style. A repeated measures general linear model analysis was performed using button and device type as within-subject factors and texting style as a between subject factor to determine which main and interaction effects influenced RPE. The model was calculated with an alpha of 0.05.

Post-hoc Tukey interval tests were performed to determine if there is a significant difference between the different device types, and the different texting styles, with regards to RPE. A linear regression was performed to determine any relationship between thumb length and typing speed. A one-way general linear model analysis was performed in order to determine any gender effects. The model was calculated with an alpha of 0.05.

3.8.4 Kinematics and Style:

In order to determine if there is any relationship between the kinematic summary variables and the texting style or device class, a series of one-way general linear models with texting style, or device class as a factor for each of the variables and each of the joints within those variables. Tukey post-hoc tests were performed in order to determine if there was any significant difference between styles or device classes. The models were calculated with an alpha of 0.05.

3.8.5 Refinement of Texting Taxonomy:

In order to explore the differences between styles, preliminary identification of texting styles was determined qualitatively. However a more quantitative method of assigning groups within a taxonomy can be achieved using an algorithm called the Gustafson-Kessel (GK) Clustering Algorithm (Babuška et al, 2002). This algorithm creates fuzzy rules for separating subjects into different groups based on the optimization of a distance norm. The number of groups can then be changed to maximize the amount of variance accounted for in the model. The mean angle, total angular range of motion, the 5th and 95th percentile of the total range of motion, and the time normalized path length for the three axes of the CMC and wrist joint, as well as the flexion/extension axis of the MP and IP joints achieved over the course of the kinematic trials were fed into the algorithm and from this, subjects were clustered together into different groups based on these variables. This allowed us to partition subjects into the different taxonomy categories based on the kinematic variables identified. And this in turn was compared to the groups determined through qualitative observation. Code for the clustering algorithm in included in Appendix D.

Style group membership was not changed to reflect the results from the clustering algorithm

ID #	Gender	Style	Height (cm)	Weight (kg)	Age	Palm Length	Hand Thickness	Digit 3 Length	Hand Length	Hand Girth	Thumb Length	Extension	IP Flexion	MP Flexion	CMC Flexion	Abduction	Opposition
01	M	Claw	180.3	83.9	25	115	25	77	192	89	127	30	98	59	30	88	147
02	M	Claw	195.6	110.0	24	127	25	90	217	110	120	20	92	55	25	75	135
03	M	Claw	188.0	92.6	24	110	25	85	195	90	100	30	65	50	15	75	140
04	M	Claw	190.5	86.2	26	150	25	90	240	90	110	29	90	65	30	75	165
06	M	Claw	172.0	72.6	24	105	20	75	180	75	100	30	80	75	25	88	105
07	M	Claw	183.0	88.5	26	110	20	90	200	85	115	20	80	75	30	85	120
09	M	Claw	180.3	79.4	25	100	20	85	185	90	120	45	90	60	20	67.5	150
11	M	Claw	182.9	74.8	24	105	17	75	180	85	105	25	70	55	15	67	120
13	F	Claw	157.5	45.4	23	90	12	70	160	75	85	17	80	100	5	70	115
14	M	Claw	185.4	86.2	23	105	20	75	180	80	112	15	85	60	35	60	120
15	M	Claw	190.5	90.3	25	108	20	90	198	82	115	35	90	65	20	80	113
16	M	Claw	182.9	81.7	24	109	23	80	189	86	106	20	85	55	15	70	105
17	F	Claw	165.1	56.7	20	90	20	74	164	76	94	32	65	60	29	63	121
		Average:	181.1	80.6	24.1	109.54	20.92	81.23	190.77	85.62	108.38	26.77	82.31	64.15	22.62	74.12	127.38
		SD:	10.6	16.2	1.6	15.52	3.77	7.36	21.05	9.25	11.66	8.36	10.40	13.08	8.50	9.09	18.47
18	F	Slide	162.6	70.8	27	100	20	75	175	74	105	45	65	55	30	89	110
19	F	Slide	185.4	68.0	23	95	15	75	170	80	100	16	90	60	27	60	120
21	F	Slide	160.0	49.9	19	100	15	75	175	70	112	15	80	75	25	43	110
22	F	Slide	155.0	47.6	19	60	15	74	134	68	88	17	90	55	10	57	121
23	F	Slide	160.0	61.2	18	86	15	75	161	72	83	30	90	50	10	50	110
24	M	Slide	184.0	76.0	30	110	15	75	185	85	110	30	85	65	5	50	120
25	F	Slide	165.1	59.0	22	90	15	77	167	75	80	16	90	67	35	87	104
26	F	slide	167.6	56.7	21	80	17	70	150	75	90	20	85	40	30	57	120
		Average:	167.5	61.2	22.4	90.13	15.88	74.50	164.63	74.88	96.00	23.63	84.38	58.38	21.50	61.63	114.38
		SD:	11.3	10.0	4.2	15.31	1.81	2.00	16.17	5.46	12.39	10.60	8.63	10.88	11.38	17.14	6.59

Table 4: Participant hand measurements and joint active ranges of motion

Chapter 4: Results

4.0 Results

4.1 Initial Participant Measurements

Prior to participating in the study, measurements of hand dimension and joint active range of motion, shown in Table 4 was taken for each participant.

4.2 Key-press Force

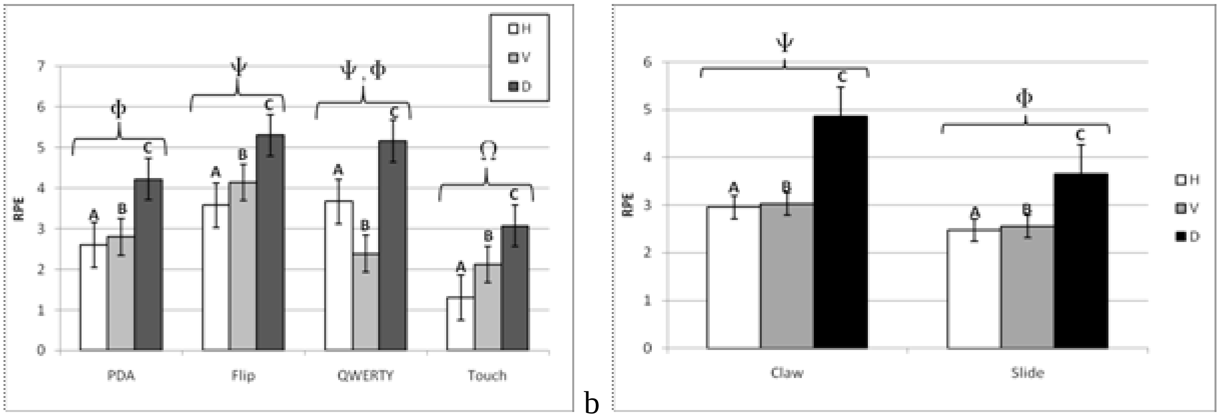
Average key-press forces for the QWERTY Keyboard, flip phone, and PDA were 2.6N, 2.83N, and 1.62N respectively. The touch screen phone does not have a required key-press force as it is activated by a change in surface capacitance. However, some users may press harder than necessary when using the touch screen if they are having trouble engaging the keys because of a film of dirt and oil interfering with the connection between the screen and the thumb however there is really no reliable way of determining what would be the standard force under these conditions since there is no clearly defined force cutoff that will result in the engagement of the key. So for the purpose of this study, the screen was kept clean, and it was assumed that zero force was required.

4.3 Dynamic Tasks

Dynamic tasks were performed by 20 subjects, 12 that use the claw texting style, and 8 that use the slide texting style. For this part of the study, participants moved their thumb as fast as possible for 10 seconds between two keys in a vertical, horizontal, and diagonal direction starting from the bottom right hand key of the keyboard. This was repeated for four different types of handheld devices, a PDA, flip phone, touch screen phone, and a candy bar phone with a full QWERTY keyboard. They then rated their discomfort in performing the task on a 0-10 visual analog scale. The results of this rating are shown in Table 5. The total number of key presses was then divided by the time of 10 seconds to get a typing speed, the results of which are shown in Table 6, expressed as key presses/second, or Hz.

		Rating of Percieved Effort																							
		QWERTY						Flip Phone						PDA						Touch Screen					
		H		V		D		H		V		D		H		V		D		H		V		D	
Participant	Style	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
01	Claw	2.45	5.1	0.86	0.89	3.07	3.59	2.45	1.58	3.77	5.4	3.74	4.86	0.02	0.02	0.98	0.87	0.4	1.87	0.04	0.07	1.08	0.75	1.52	2.22
02	Claw	3.53	4.64	2.83	5.74	1.92	2.91	3.89	4.76	3.51	7.23	6.39	8.01	5.44	3.72	4.3	6.62	4.4	2.96	1.5	0.62	0.63	2.26	1.07	1.15
03	Claw	8.05	6.52	6.01	4.84	8.57	8.35	1.96	1.35	1.03	5.68	3.63	0.42	1.16	3.22	0.46	2.45	6.37	5.95	0.02	0.48	2.77	1.31	8.08	6.51
04	Claw	8.9	6.42	3.71	3.58	10	10	4.74	5.99	5.59	5.71	8.44	7.77	9.18	7.82	4.36	5.06	5.37	8.01	8.49	8.4	3.97	6.79	9.17	8.81
05	Claw	1.67	2.12	0.28	0.32	2.69	2.98	1.49	2.05	2.85	3.9	4.81	4.07	2.76	2.35	1.89	1.52	2.65	3.28	0.86	1.68	2.56	1.7	3.01	2.75
06	Claw	5.75	6.77	0.59	0.03	6.36	4.06	6.17	5.1	1.81	2.6	7.19	5.83	3.52	3.27	0.01	0.02	5.58	4.42	0.92	0.01	0.75	2.97	3.26	2.08
07	Claw	0.03	0.55	0.01	0.02	0.02	0.27	0.02	0.23	0.84	0.74	0.91	0.97	0.03	0.02	0.92	0.39	0.03	0.32	0.01	0.28	0.27	0.57	0.88	0.29
08	Claw	3.84	6.98	0.01	0.41	10	10	3.45	4.62	5.41	5.49	9.11	9.89	0.12	0.35	2.88	2.85	5.29	7.45	0.01	0.01	0.29	3.31	2.92	6.36
09	Claw	3.21	3.93	3.7	2.97	5.63	8.78	8.51	10	9.71	10	10	10	3.32	5.27	5.39	2.7	4.07	5.71	0.48	7.14	4.49	7.17	1.83	3.33
10	Claw	0.47	0.54	0.06	1.47	2.4	2.62	2.87	3.37	1.59	1.41	4.75	4.32	0.55	0.37	1.78	1.34	4.94	5.5	0	0	0.33	0.51	1	0.96
11	Claw	1.75	0.25	3.79	5.41	3.1	1.96	1.87	0.8	0.65	4.38	2.29	3.01	1.5	2.61	3.44	4.16	2.98	5.43	0	0.34	5.58	3.27	1.89	3.18
12	Claw	1.62	4.02	3.76	1.75	3.23	6.04	2.31	1.82	3.11	2.37	4.81	6.73	1.56	1.35	2.53	3.27	4.87	4.27	1.07	0.87	1.42	0.99	3.95	3.93
13	Claw	8.08	5.93	5.92	6.53	9.32	9.36	6.88	7.99	8.49	9.03	10	10	3.07	4.21	5.24	5.6	6.34	6.36	2.26	2.19	3.96	4.24	4.25	5.77
	Mean:	**3.8**	**4.14**	**2.43**	**2.61**	**5.1**	**5.46**	**3.59**	**3.82**	**3.72**	**4.92**	**5.85**	**5.84**	**2.48**	**2.66**	**2.63**	**2.83**	**4.1**	**4.73**	**1.2**	**1.7**	**2.16**	**2.76**	**3.29**	**3.64**
	SD:	**2.99**	**2.51**	**2.23**	**2.37**	**3.42**	**3.43**	**2.4**	**2.94**	**2.88**	**2.78**	**2.94**	**3.26**	**2.59**	**2.31**	**1.81**	**2.06**	**2.05**	**2.19**	**2.3**	**2.79**	**1.84**	**2.22**	**2.62**	**2.54**
14	Slide	10	10	8.65	6.86	10	13	6.72	8.98	10.7	12.9	8.92	9.8	9.01	10	10	10	7.66	10	2.99	1.68	5.21	5.22	6.93	5.66
15	Slide	1.86	2.34	1.86	2.35	2.44	1.61	1.5	1	1.09	3.09	1.82	1.82	2.73	0.92	1.14	1.23	1.73	2.32	1.72	2.98	1.22	1.97	2.42	1.44
16	Slide	4.17	1.75	2.76	3.16	3.18	4.86	1.93	1.93	1.93	1.95	1.94	3.38	1.49	2.48	2.84	1.54	2.88	3.96	0.95	0	0	0	1.39	0.97
17	Slide	0.35	1.25	0	0	5.6	3.52	0.84	0.91	2.85	0.34	5	5.12	0	0.55	0.01	0.01	0.8	0.48	0.01	0.03	0.02	0.01	0	0.47
18	Slide	2.91	2.27	2.02	2.02	3.59	3.17	2.4	3.4	2.2	1.5	2.67	2.24	2.83	1.7	2.44	2.98	3.22	2.88	2.09	1.9	3.11	2.22	3.28	2.62
19	Slide	1.58	3.15	0.02	0.34	2.31	4.3	7.42	6.19	6.19	6.6	4.56	4.54	1.87	3.26	0.75	2.58	5.25	9.67	0	0.01	0.23	1.65	3.14	4.53
20	Slide	0.45	0.46	0	0	1.98	1.96	0.01	0.01	0	0	1.21	0.95	0.03	0.01	0.02	0.01	1.82	0.95	0	0	0	0	0	0
	Mean:	**3.05**	**3.03**	**2.19**	**2.1**	**4.16**	**4.64**	**2.97**	**3.2**	**3.57**	**3.76**	**3.73**	**3.98**	**2.57**	**2.7**	**2.46**	**2.62**	**3.34**	**4.32**	**1.11**	**0.94**	**1.4**	**1.58**	**2.45**	**2.24**
	SD:	**3.35**	**3.19**	**3.07**	**2.44**	**2.85**	**3.88**	**2.91**	**3.27**	**3.7**	**4.57**	**2.69**	**2.96**	**3.06**	**3.41**	**3.5**	**3.45**	**2.38**	**3.94**	**1.19**	**1.23**	**2.03**	**1.88**	**2.39**	**2.14**

Table 5: Rating of perceived exertion for dynamic tasks.



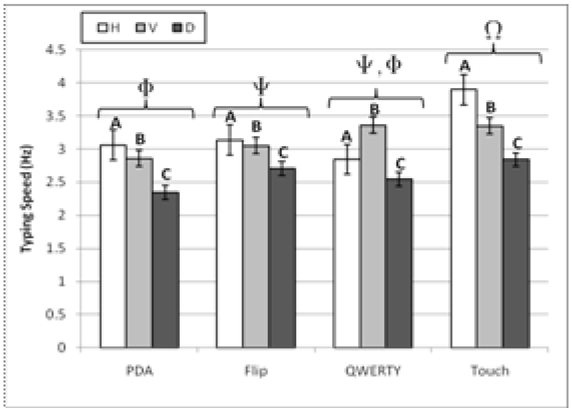
a b

Figure 10: Average(±SE) Rating of Perceived Effort (scale 0-10) for rapid thumb motion between two keys in the horizontal (H), vertical (V), and diagonal (D) directions from the bottom right-hand key of the keyboard grouped by a) device type, and b) texting style. Vectors labelled with different letters indicate a statistically significant difference (P<0.05). Device types labelled with different Greek letters indicates a statistically significant difference. Texting styles labelled with different Greek letters indicate a statistically significant difference.

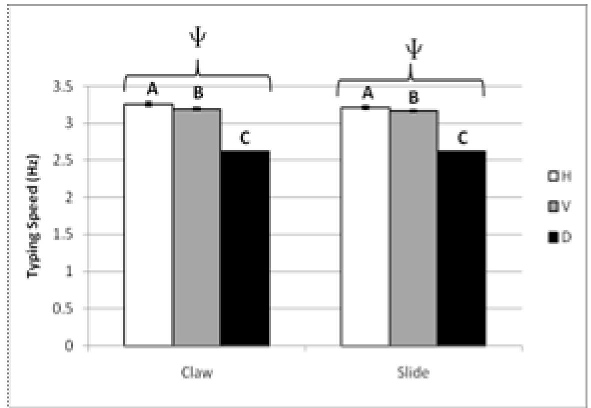
As seem in Figure 10, the diagonal motion, which is the motion requiring the greatest degree of IP flexion, requires 25 to 100 percent more physical effort over other motion vectors and is the most difficult task, regardless of device type or texting style. Overall, users reported that the flip phone required the most effort, about 66 to 350 percent more than the touch screen phone which required the least effort for all motion vectors. It should be noted that these also require the most and least key-press force respectively. Analysis shows that device class, motion vector, and texting style are all statistically significant (P<0.0001) factors in the required effort for dynamic tasks. Post hoc tests also confirm that there is a significant difference between the two styles (P=0.001) and motion vectors (P<0.0001). However, the QWERTY keyboard is not significantly different from the flip phone (P=0.167) or PDA ((P =0.262), but they are significantly different from each other (P=0.001). All devices are significantly different from the touch screen phone (P<0.0001). There is a significant interaction between vector and device class (P=0.029) specifically, the combination of the claw style and the flip phone results in a very high rating of perceived effort for the diagonal motion when compared to the other combinations of style and device. Overall for dynamics tasks, the slide texting style requires 20 to 43 percent less effort. Analysis also shows a significant (P<0.001) gender effect, and an adjusted R squared value of 0.029.

		Typing Speed (Keystrokes/second)																							
		QWERTY						Flip Phone						PDA						Touch Screen					
		H		V		D		H		V		D		H		V		D		H		V		D	
Participant	Style	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
01	Slide	2.5	2.5	2.7	3.4	2.6	2.3	3.2	3.1	3.3	2.8	2.7	3.1	2.4	2.7	1.7	2.4	1.8	2.1	3.7	4.2	3.5	3.5	3	2.6
02	Claw	2.5	2.9	2.9	3	2.4	2	2.6	3	3	3.1	2.4	2.5	2.5	2.7	1.9	2.5	2.5	2	4.2	4.5	3.4	3.7	2.7	2.8
03	Claw	2.7	2.8	2.7	3.2	2.3	2.2	3.3	3.1	3	3	2.4	2.6	3	3.3	2.8	2.8	2.2	2.4	4.3	4.3	3.9	4	3.1	3.7
04	Claw	2.5	2.9	3.3	3.3	2.4	2.2	2.8	3.2	2.7	2.8	2.2	2.6	2.5	2.9	2.5	3.1	2.1	2.1	4.2	4.3	2.6	3	2.5	2.3
05	Claw	3.7	3.8	4.2	3.7	3.4	3.1	3.9	4	3.7	4	3.2	3	3.8	3.7	3.4	3.5	2.6	2.9	4.4	4.4	3.6	4.1	3.6	3.4
06	Claw	2.8	3.1	3.6	3.8	2.6	2.5	3.1	2.8	3.1	3.3	2.7	2.8	3.5	3.2	3.1	3	2.8	2.8	4.2	4.1	3.3	3.2	2.8	2.7
07	Claw	2.6	2.5	3.3	3.5	1.7	2.2	2.4	2.6	3.1	3	2.2	2.1	2.6	2.4	2.6	2.7	1.7	2.1	2.7	3.4	3.1	2.7	2.4	2.6
08	Slide	2.9	2.9	2.9	3.4	2.4	2.6	2.9	2.9	2.7	3.2	2.3	2.4	2.3	2.5	1.9	2	1.9	2	3.1	3.9	2.7	3.2	3	2.9
09	Claw	2.8	3.2	3.9	4	2.9	2.6	2.6	3.4	3.5	3.5	3.3	3	4.2	4.1	3.8	3.7	3.5	3.2	4.1	4.9	3.8	4	2.7	3.6
10	Claw	2.3	2.7	3	3.2	2.3	2.2	2.5	2.4	2.7	2.6	2.2	2.4	2.4	2.8	2.5	2.5	1.9	2.1	3.9	3.9	2.5	3.2	2.5	2.7
11	Slide	3	3.6	3.7	3.7	3	3.2	3.9	3.9	3.8	3.9	3.7	3.9	3.9	3.6	4.1	4.2	3.1	3.3	3.2	3.9	4.1	3.9	2.8	3.2
12	Claw	2.9	3.1	3.4	3.4	2.6	2.5	3	3	3	2.9	2.8	2.6	2.8	3.2	2.6	2.7	2.3	2.7	4	4.3	4	4	3.1	3.6
13	Slide	3	3	2.8	2.9	2.3	2.4	3	3.2	3	2.9	2.6	2.7	3.3	3.3	2.9	2.7	1.8	1.6	3.9	3.9	2.9	3.2	2.4	2.6
14	Slide	2.7	2.7	2.9	3.1	2.8	2.8	2.6	2.9	2.4	2.4	2.2	2.5	2.3	2.4	1.7	2.2	1.4	1.9	2.2	2.7	2.2	2.7	2.1	2.1
15	Claw	3	3.3	3.6	4.1	3.9	3.9	4.2	4	3.6	4.2	3.6	3.7	3.4	3.7	3.8	3.8	3.2	3.2	4.1	4.4	4	4.3	2.9	4.1
16	Claw	2.2	2.5	1.7	2.5	1.8	2	2.3	3	2.5	1.9	2.4	2.4	2.4	3.3	2.4	2.4	2.1	2.1	3.8	3.7	2.5	3.2	2.3	2.9
17	Claw	2.7	2.6	3.7	3.6	2.4	2.4	3.5	3.8	3.1	3.1	2.3	2.6	3.8	3.2	2.9	3.2	2.5	2.6	2.6	3.6	2.5	3.3	2	2.5
18	Slide	2.2	2.1	4.2	2.8	2.1	1.9	2.5	3	2.3	2.8	2.6	2.9	2.4	2.3	2.4	2.3	1.7	1.7	3.6	4.2	2.4	3	2.4	2.7
19	Claw	2.5	2.8	3.8	3.3	2.2	2.7	3.2	2.7	2.5	2.9	2.6	2.5	2.3	3.1	2.9	2.8	1.9	2.4	4.2	3.7	3.1	3.5	2	2.6
20	Slide	3.4	3.9	3.9	4.3	2.9	3.1	3.7	4.2	3.7	2.9	2.7	2.7	4.3	3.9	3.7	4.2	2.6	3.1	4.4	4.7	4	4.2	3.8	3.9

Table 6: Typing Speed for dynamic tasks expressed in keystrokes/second for two trials



a



b

Figure 11: Average (±SE) Typing Speed (Hz) for rapid thumb motion between two keys in the horizontal (H), vertical (V), and diagonal (D) directions from the bottom right-hand key of the keyboard grouped by a) device type, and b) texting style. Vectors labelled with different letters indicate a statistically significant difference (p<0.05). Device types labelled with different Greek letters indicates a statistically significant difference.

In Figure 11 it is shown that in all cases the diagonal motion is 9 to 45 percent slower than other motions. In most cases the horizontal motion is the fastest, except for the QWERTY device in which the vertical motion is fastest. Analysis shows that the device class, motion vector, and the interaction between the variables are all statistically significant factors in the average typing speed (P<0.0001). However texting style was not a significant factor ((P =0.5959). Post hoc test confirm that there is no significant difference between texting styles with regards to speed (P=0.600). It also confirms that most device types and all motion vectors are significantly different from each other. However, the same exception exists with regards to speed as in dynamic RPE, that being that the QWERTY keyboard is not significantly different from the flip phone (P=0.976) or PDA ((P =0.082), but they are significantly different from each other(P=0.02). Once again, all devices are significantly different from the touch screen phone (P<0.0001) which allows for a 33 to 45 percent faster typing speed than the other devices. Motion difference between motion vectors has a significance level of (P<0.0001). Results show no significant (P=0.186) gender effect.

4.4 Static Tasks

Static tasks were performed by 20 subjects, 12 that use the claw texting style, and 8 that use the slide texting style. Subjects were asked to hold down one of four buttons at the four corners of the operational workspace for the device for 20 seconds. They were then asked to rate their discomfort while performing the static hold on a visual analog scale of 0-10, the results of which are shown in Table 7.

Participant	Style	Rating of Perceived Effort																															
		QWERTY								Flip Phone								PDA								Touch Screen							
		A		B		C		D		A		B		C		D		A		B		C		D		A		B		C		D	
		1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
01	Claw	1.64	3.4	3.36	4.61	1.49	2.45	2.86	5	1.3	1.29	1.81	1.32	2.75	3.13	1.8	2.02	0.63	3.45	1.32	5.8	1.89	1.68	6.96	7.56	0.78	3.19	3.19	0.95	1.93	1.65	1.56	4.45
02	Claw	4.19	2.9	5.12	4	3.43	4.24	3.48	4.77	4.58	4.85	5.01	5.26	6.54	5.77	6.14	4.75	4.93	4.14	3.34	3.07	4.37	4.73	3.91	2.76	0.02	0.1	0.47	0.5	0.98	0.07	0.44	0.34
03	Claw	4.71	5.99	5.05	8.09	3.75	8.73	6.01	8.24	2.26	1.75	1.05	1.34	3.14	2.7	4.6	3.47	0.63	0.03	1.04	1.03	0	0.04	4.62	1.46	0.08	2.16	0	0.38	0	0	0	0.54
04	Claw	5.43	4.14	8	4.97	5.94	7.45	8.47	8.91	7.65	6.26	7.13	8.59	12.7	10	10	10	4.3	7.64	10	9.8	7.43	8.69	8.85	7.75	5.81	5.63	9.43	8.75	8.25	7.15	8.34	8.64
05	Claw	5.84	6.32	4.44	3.82	4.45	2.47	2.37	2.89	3.35	3.82	3.4	3.9	5.18	4.35	4.07	3.38	4.79	4.62	3.55	4.11	3.73	3.51	4.14	3.96	1.7	1.67	1.9	2.55	1.87	1.89	1.71	1.81
06	Claw	0.03	0	2.98	0.31	4.54	4.05	0.86	1.31	1.69	3.3	1.71	1.55	5.79	5.67	4.58	3.38	0	0.01	0	0	0.04	0.04	2.16	1.13	0	0	0.35	0.55	0.39	0.71	2.75	1.21
07	Claw	0.4	0.02	0	0	0.21	0.04	0.25	0.01	0.21	0.23	0	0.22	0.02	0	0.02	0.28	0.07	0.02	0.02	0.02	0	0.24	0.01	0.01	0.08	0.26	0	0.03	0.01	0.02	0.01	0.03
08	Claw	0.85	0.5	3.75	3.93	0.01	0.45	2.38	4.92	0.56	0.74	2.34	1.94	2.42	1.94	1.41	0.94	3.39	4.92	1.84	3.35	0.01	0.01	1.17	2.04	1.73	0.92	0.69	1.52	0.01	0.01	0	0.46
09	Claw	0.41	1.74	2.04	0.51	0.86	1.35	0.51	1.23	1.65	1.76	2.03	2.4	0.4	0.13	4.26	4.82	0.83	1.72	0.87	0.54	4.09	0.55	3.73	5.77	1.07	1.03	1.86	1.87	0.27	0.53	3.85	1
10	Claw	3.01	4.43	0.07	0.07	0.64	1.34	2.75	5.19	0.4	1.94	1.16	1.16	6.31	5.47	1.62	2.84	0.37	1.02	1.58	1.48	2.78	2.41	2.85	0.02	0.36	0.08	0.01	0	4.04	1.82	3.31	2.27
11	Claw	4.09	3.98	2.97	5.34	0.89	1.98	5.98	4.6	0.43	1.65	3.16	2.26	1.44	3.31	1.46	2.4	1.41	2.74	4.45	3.72	1.95	1.5	6.9	6.88	1.22	0.58	3.67	2.59	2.39	0.65	7.68	5.52
12	Claw	6.17	2.86	8.59	5.33	3.43	3.4	12	0.4	5.55	4.81	5.1	4.61	4.04	5	2.78	5.82	6.51	3.35	8.9	5.7	5.16	2.72	3.21	7.66	3.04	7.22	5	6.88	5.02	5.36	4.42	4.29
13	Claw	4.21	5.86	5.89	5.45	5.44	5.15	7.15	6.87	5.42	5.45	5.03	5.37	6.87	7.81	4.56	8.52	6.65	6.45	5.71	5.71	4.98	5.71	5.87	6.45	0.03	0.01	0.1	0.2	1.25	1.22	2.03	1.06
	Mean:	**3.15**	**3.24**	**4.02**	**3.57**	**2.7**	**3.32**	**4.23**	**4.18**	**2.7**	**2.91**	**2.99**	**3.07**	**4.43**	**4.26**	**3.64**	**4.05**	**2.65**	**3.09**	**3.28**	**3.41**	**2.8**	**2.45**	**4.18**	**4.11**	**1.22**	**1.76**	**2.05**	**2.06**	**2.03**	**1.62**	**2.78**	**2.43**
	SD:	**2.23**	**2.19**	**2.6**	**2.56**	**2.09**	**2.6**	**3.48**	**2.87**	**2.41**	**1.95**	**2.05**	**2.35**	**3.39**	**2.85**	**2.6**	**2.78**	**2.51**	**2.48**	**3.23**	**2.87**	**2.4**	**2.64**	**2.47**	**3.02**	**1.65**	**2.3**	**2.75**	**2.73**	**2.44**	**2.2**	**2.75**	**2.57**
14	Slide	0.76	1.33	2.54	1.38	0.33	5.34	8.24	6.21	3.41	2.9	3.35	1.36	4.9	4.83	9.73	10	0.59	1.28	2.55	0.98	1.32	0.6	3.32	3.22	0.25	2.39	0.63	1.65	1.1	0.63	2.51	5.16
15	Slide	0.04	0.42	0.02	0.03	0.02	0	0.04	0.03	0.08	0.05	0.02	0.25	0.58	0.25	0.02	0.28	0.05	0.31	0.02	0.37	0.03	0.03	0.34	0.34	0.03	0	0.03	0.01	0.02	0.04	0	0
16	Slide	5.54	1.51	0.74	4.91	5.53	3.24	2.79	3.58	2.31	3.24	1.68	1.69	1.68	6.28	4.91	5.21	6.8	7.65	7.6	8.51	5.64	7.68	5.65	7.67	1.02	2.12	0.69	2.01	4.99	4.84	1.5	2.12
17	Slide	0.04	0.01	0.36	0	0	0	0	0.4	2.59	2.12	2.11	1.44	3.2	7.32	5.77	5.82	0.02	0	0.01	0.52	0.68	0.03	3.25	4.07	0	0	0	0.01	0.01	0	0.35	1.42
18	Slide	2.17	2.68	1.68	2.49	1.86	2.2	0.97	1.45	2.87	2.35	2.57	2.95	2.74	2.68	2.73	3.48	2.49	2.98	2.55	2.72	2.33	4.3	2.75	2.88	2.81	3.34	2.59	2.18	2.26	2.12	2.8	2.72
19	Slide	0.92	1.4	1.9	2.74	0.23	2.7	0.98	2.43	0.91	1.91	1.33	1.65	2.61	2.88	1.93	3.6	3	2.98	4.15	4.51	3.92	3.19	4.28	4.9	0.91	0	0	0.02	0	0.02	0	0.06
20	Slide	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mean:	**1.35**	**1.05**	**1.03**	**1.65**	**1.14**	**1.93**	**1.86**	**2.01**	**1.74**	**1.8**	**1.58**	**1.33**	**2.24**	**3.46**	**3.58**	**4.06**	**1.85**	**2.17**	**2.41**	**2.52**	**1.99**	**2.26**	**2.8**	**3.3**	**0.72**	**1.12**	**0.56**	**0.84**	**1.2**	**1.09**	**1.02**	**1.64**
	SD:	**2**	**0.97**	**1.01**	**1.86**	**2.05**	**2.05**	**2.98**	**2.28**	**1.39**	**1.29**	**1.25**	**0.98**	**1.66**	**2.83**	**3.5**	**3.44**	**2.51**	**2.74**	**2.81**	**3.09**	**2.13**	**2.95**	**2.03**	**2.65**	**1.02**	**1.45**	**0.95**	**1.05**	**1.88**	**1.82**	**1.24**	**1.9**

Table 7: Rating of Perceived Effort for static holds.

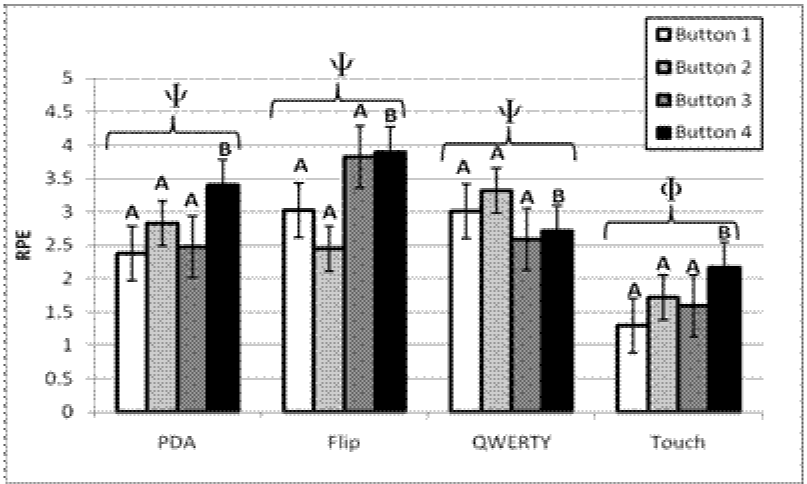


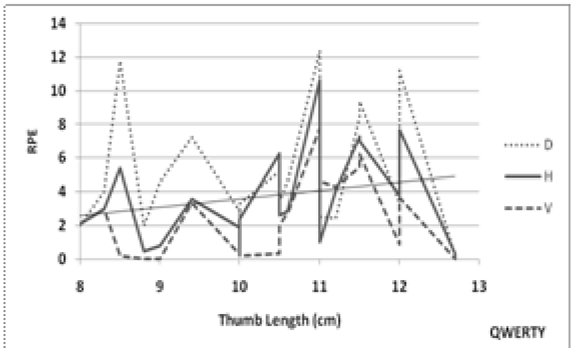
Figure 12: Average (±SE) Rating of Perceived Effort (scale 0-10) for static holds of the keys at the four corners of the operational workspace of the keyboard with keys 1 through 4 representing the top left, top right, bottom left, and bottom right corners respectively. Buttons labelled with different letters indicate a statistically significant difference. Device types labelled with different Greek letters indicates a statistically significant difference.

The most difficult button to hold is at the bottom right corner, which requires 2 to 56 percent more effort than the other buttons (Fig 12). Overall the flip phone requires the most effort to hold the buttons and the touch screen requires the least, with the flip phone requiring 42 to 53 percent more effort than the touch screen phone. Once again, it should be noted that these also require the most and least key-press force respectively, and the flip phone requires the greatest degree of flexion. The device class (P=0.003) and button (P=0.004) are both statistically significant factors in determining the difficulty of a static hold, however there is no significant interaction effect (P=0.702) and there is no significant effect of texting style (P=0.499). Post hoc tests show that the only significant difference between device types is between the touch screen and the other devices (P<0.0001). However, there is no significant difference between the PDA and Flip Phone (P=0.877), the QWERTY and Flip Phone (P=0.601), and the QWERTY and PDA (P=0.961). Furthermore post hoc tests show that the only significant difference between buttons is between the bottom right corner, labelled button "D" and the others (P=0.03). However, there is no significant difference between buttons A and B (P=0.616), A and C (P=0.447), and B and C (P=0.993). Results show a significant (P<0.001) gender effect with an adjusted R squared value of 0.098.

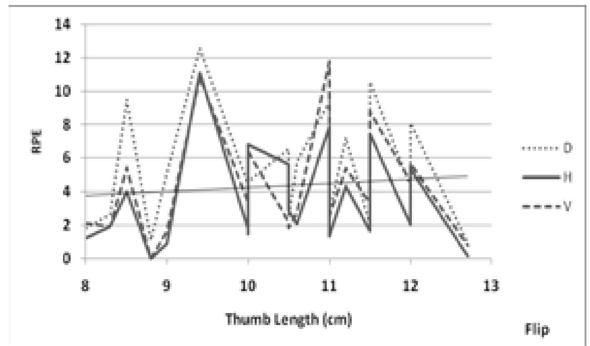
4.5 Effect of Thumb Length

Linear regression was performed to determine the effect of subject thumb length on the rating of perceived effort in static and dynamic tasks and on typing speed.

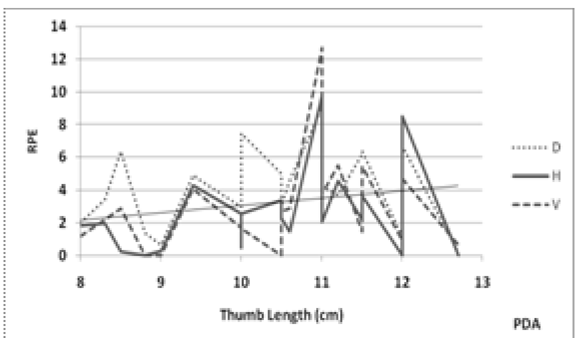
a)



b)



c)



d)

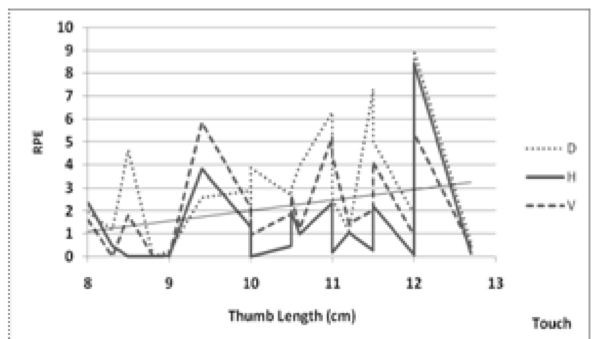


Figure 13: Average Rating of Percieved Effort for dynamic tasks plotted vs subject thumb length

Results show that there is a significant ($P<0.0001$) relationship between thumb length and the effort required to complete the dynamic tasks, this linear model has an R squared value of 0.036, so in practical terms there is not a very strong relationship between RPE and thumb length. There was no significant interaction effect between thumb length and device type. The required effort increased with thumb length.

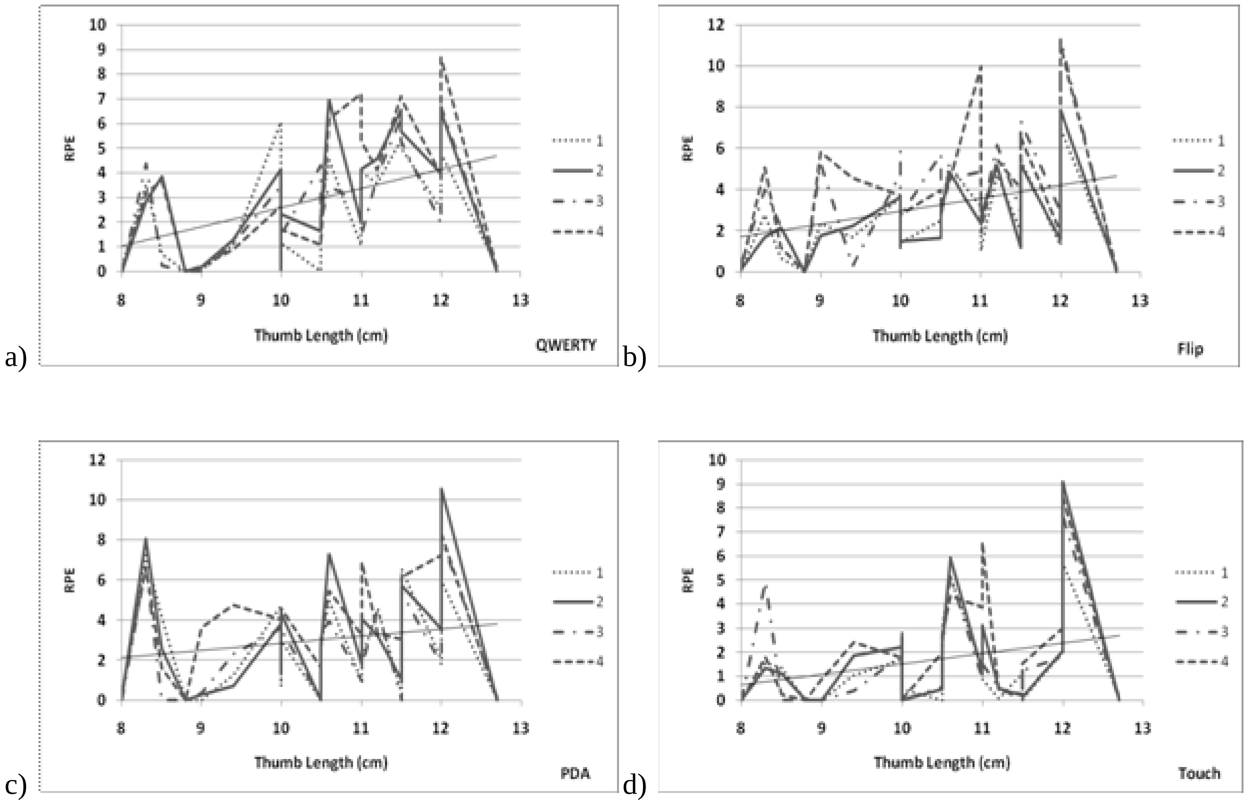


Figure 14: Average Rating of Percieved Effort for static tasks plotted vs subject thumb length

Results show that there is a significant (P<0.0001) relationship between thumb length and the effort required to complete the static tasks. However, the linear model using thumb and device type as factors only has an R squared value of 0.078, so in practical terms there is not a very strong relationship between static RPE and thumb length even though it is significant. There was no significant interaction effect between thumb length and device type. As with dynamic RPE, there appears to be a trend where RPE increases with thumb length.

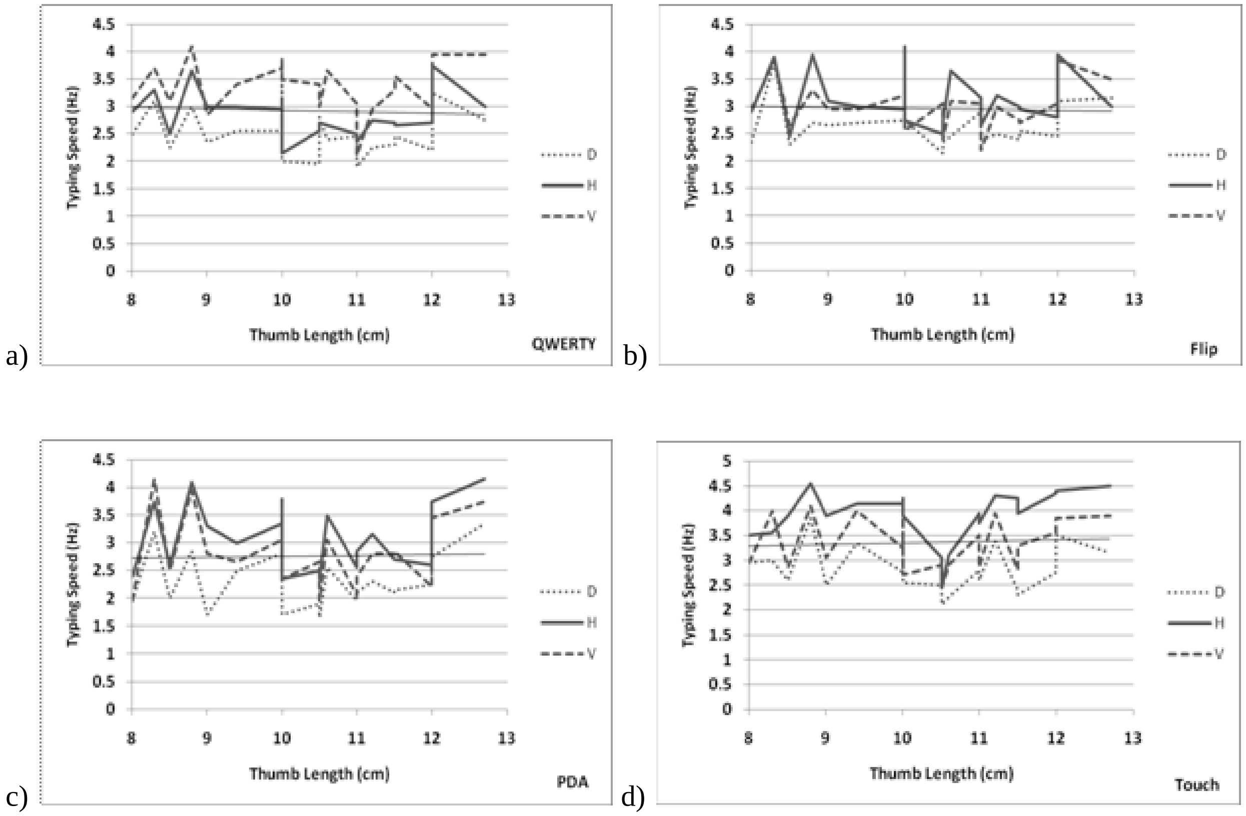


Figure 15: Average Typing Speed in keystrokes per second (Hz) for dynamic tasks plotted versus subject thumb length

Results show that there is no significant (P= 0.975) relationship between thumb length and the average typing speed for the dynamic tasks the dynamic tasks. The linear model has an R squared value of 0.0001. However, for the QWERTY and flip phone there seems to be a trend where the typing speed will decrease with an increase in thumb length.

4.6 Kinematic Variables

The following data shown in figure 16 through 20 is a sample of processed data from a single subject.

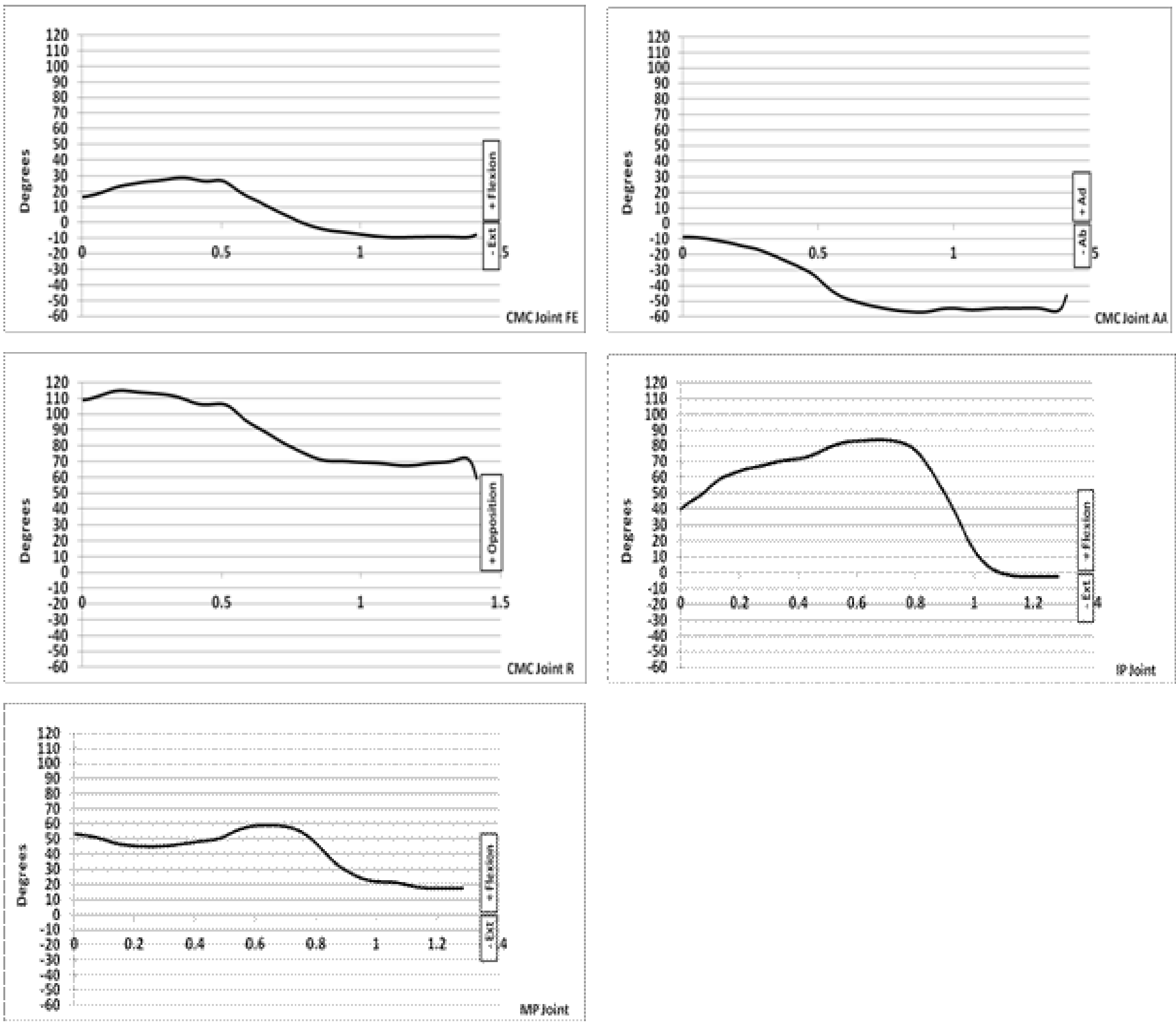


Figure 16: Processed Joint angle time history for a complete circumduction of the thumb.Charts display time history for the Flexion/Extension, Abduction/Adduction, and Rotation axes of the CMC Joint and for the Flexion/Extension axis of the MP and IP joints. Horizontal axis is seconds

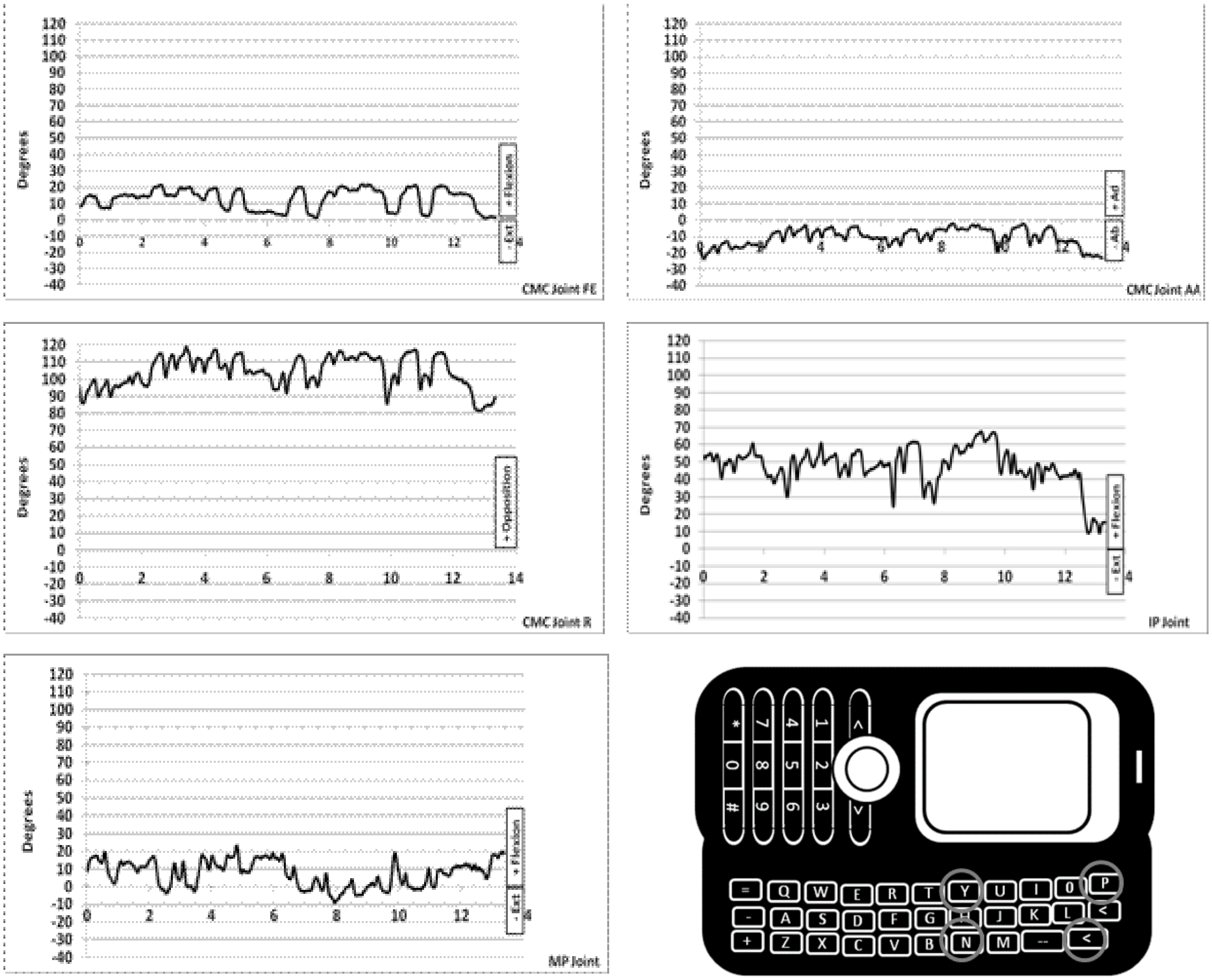


Figure 17: Processed Joint angle time history for the dynamic trial of the QWERTY Phone of the thumb with 24 key presses.Charts display time history for the Flexion/Extension, Abduction/Adduction, and Rotation axes of the CMC Joint and for the Flexion/Extension axis of the MP and IP joints.Horizontal axis is seconds

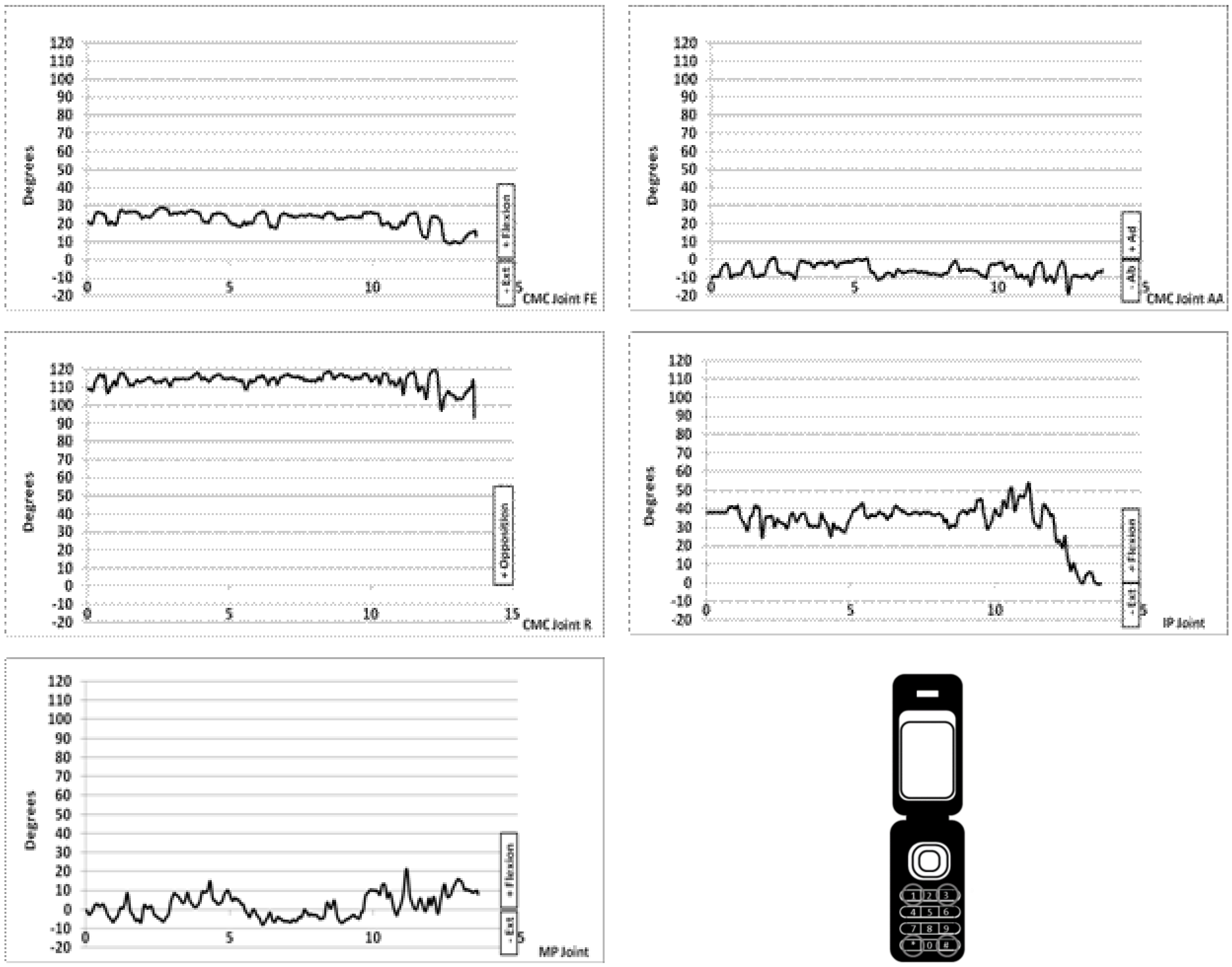


Figure 18: Processed Joint angle time history for the dynamic trial of the Flip Phone.Charts display time history for the Flexion/Extension, Abduction/Adduction, and Rotation axes of the CMC Joint and for the Flexion/Extension axis of the MP and IP joints. Horizontal axis is seconds

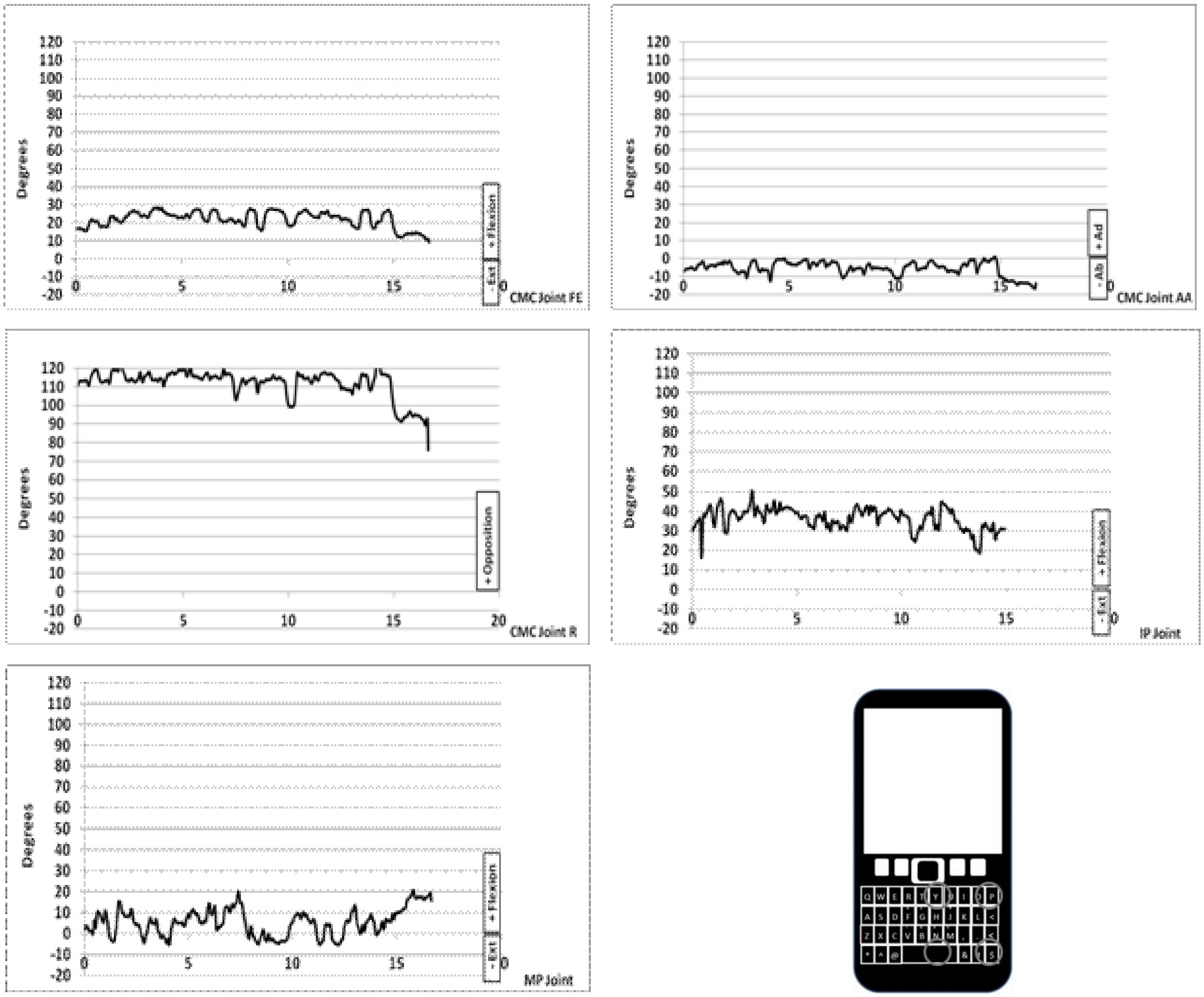


Figure 19: Processed Joint angle time history for the dynamic trial of the PDA. Charts display time history for the Flexion/Extension, Abduction/Adduction, and Rotation axes of the CMC Joint, and for the Flexion/Extension axis of the MP and IP joints. Horizontal axis is seconds

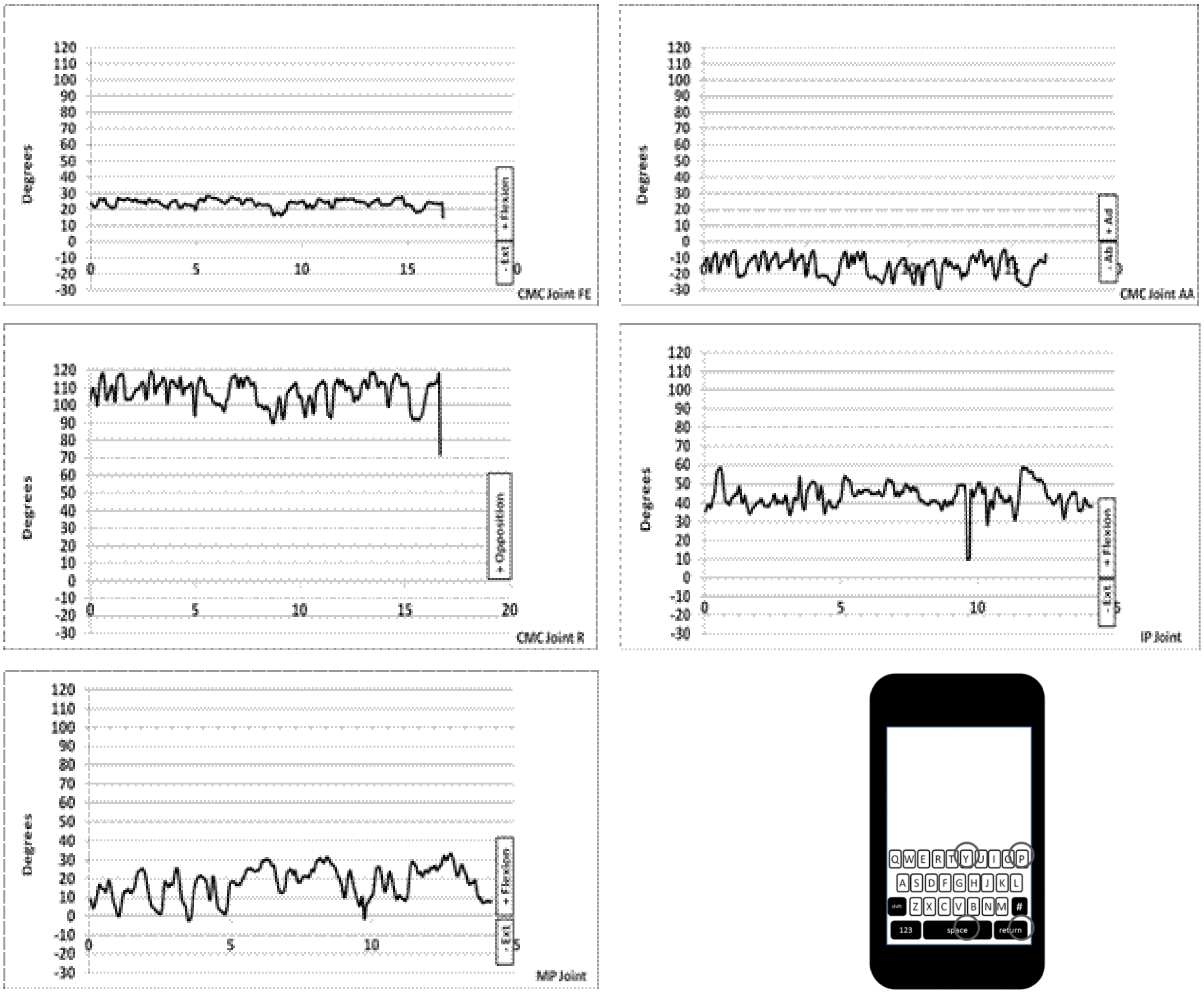
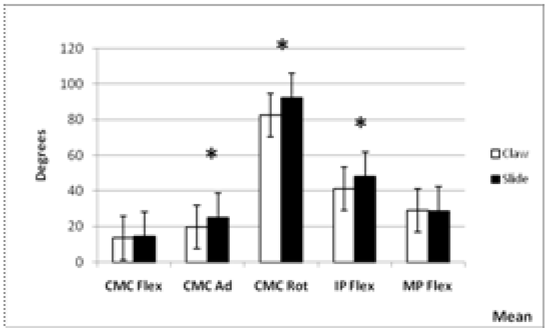


Figure 20: Processed Joint angle time history for the dynamic trial of the Touch Screen Phone. Charts display time history for the Flexion/Extension, Abduction/Adduction, and Rotation axes of the CMC Joint and for the Flexion/Extension axis of the MP and IP joints. Horizontal axis is seconds

a) 

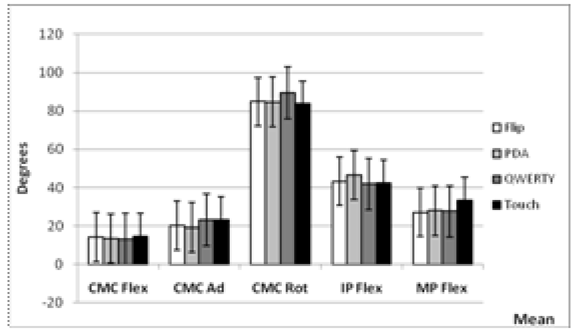
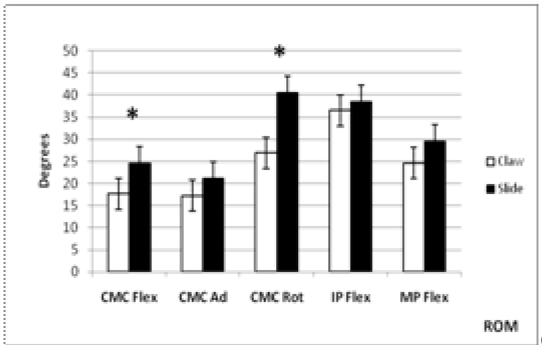
b) 

Figure 21: Average (±SE) values for mean joint angle over kinematic tasks separated by texting style and then by joint axis of rotation in the first chart and by device type and joint axis in the second chart. A larger value of joint angle coresponds to a more extended joint position. A star (*) indicates a statistically signficant difference between texting styles or device type for that value and that joint axis of rotation. Different geometric shapes in (b) indicate a statistically significant difference between device types for that joint axis of rotation. An absence of geometric shapes labelling in (b) indicates no statistical difference between device types for that joint axis of rotation.

For the mean joint angle during the kinematic tasks shown in Figure 21, results show a statistically significant difference between the slide and claw styles for the abduction/adduction and rotational axes of the CMC joint and for the flexion/extension axis of the IP joint. In all those cases, the slide style has a 13 to 25 percent higher mean joint angle. Device type appears to have no significant effect on the mean joint angle for the dynamic tasks.

c) 

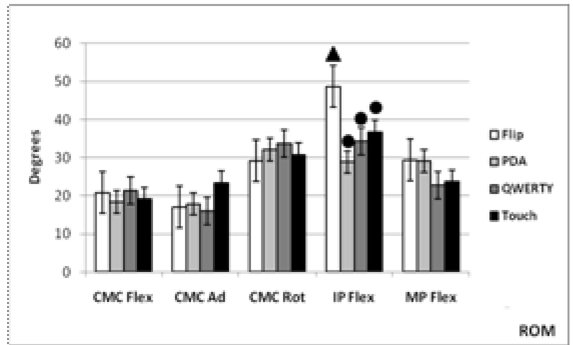
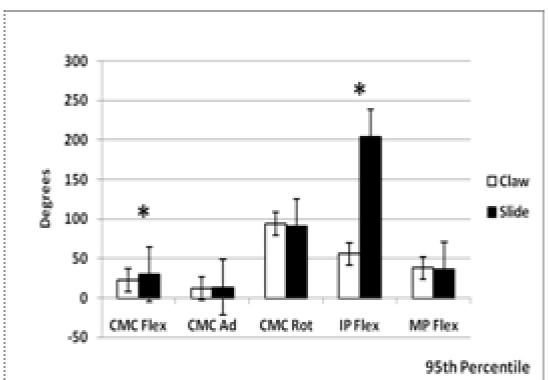
d) 

Figure 22: Average values +/- SE for angular range of motion over kinematic tasks separated by texting style and then by joint axis of rotation in the first chart and by device type and joint axis in the second chart. A star (*) indicates a statistically signficant difference between texting styles or where device type for that value and that joint axis of rotation is a statistically significant factor. Different geometric shapes in (d) indicate a statistically significant difference between device types for that joint axis of rotation. An absence of geometric shapes labelling in (d) indicates no statistical difference between device types for that joint axis of rotation.

For the total anglular range of motion during the kinematic tasks shown in Figure 22, results show a statistically significant difference between texting styles for the flexion/extension and rotational axis of the CMC joint. In both these cases the slide style has a 47 to 60 percent higher total range of motion over the duration of the kinematic tasks. Device type has no significant effect on total angular range of motion.

e) 

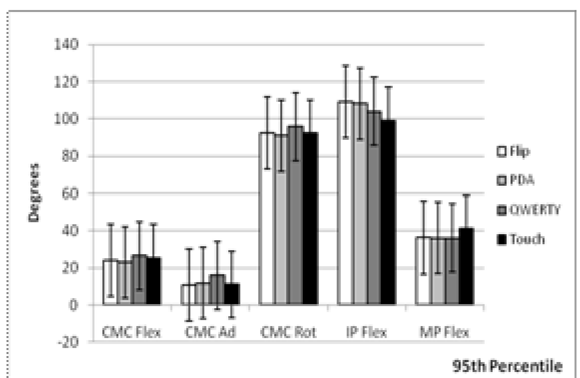
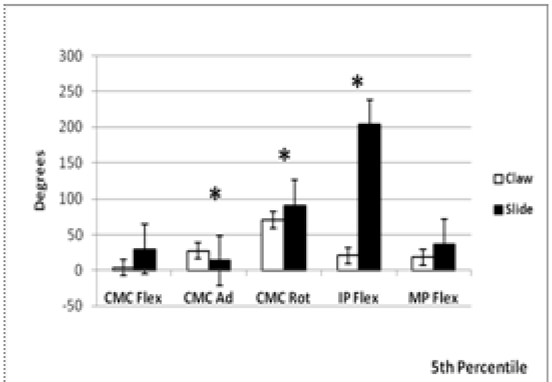
f) 

Figure 23: Average values +/- SE for the 95th percentile joint angle over kinematic tasks separated by texting style and then by joint axis of rotation in the first chart and by device type and joint axis in the second chart. A larger value of joint angle coresponds to a more extended joint position. A star (*) indicates a statistically signficant difference between texting styles or device type for that value and that joint axis of rotation. Different geometric shapes in (f) indicate a statistically significant difference between device types for that joint axis of rotation. An absence of geometric shapes labelling in (f) indicates no statistical difference between device types for that joint axis of rotation.

The value of the 95th percentile of the total angular range of motion over course of the kinematic tasks shown in Figure 23, shows a significant difference between texting styles for the flexion/extension axis of the both the CMC and IP joints. In both those cases the slide style has a 20 to 400 percent higher 95^{th} percentile value. Device type has no significant effect on the 95^{th} percentile value over the duration of the kinematic tasks.

g) 

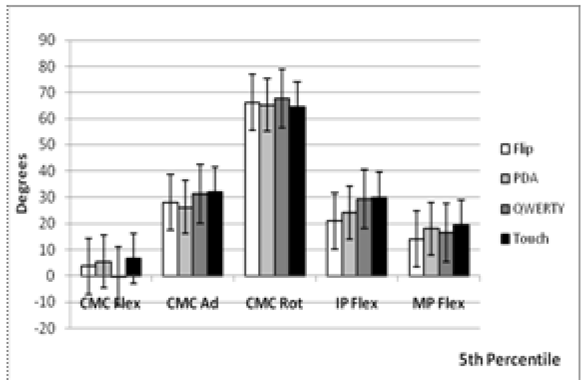
h) 

Figure 24: Average values +/- SE for the 5^{th} percentile joint angle over kinematic tasks separated by texting style and then by joint axis of rotation in the first chart and by device type and joint axis in the second chart. A larger value of joint angle coresponds to a more extended joint position. A star (*) indicates a statistically signficant difference between texting styles or device type for that value and that joint axis of rotation. Different geometric shapes in (h) indicate a statistically significant difference between device types for that joint axis of rotation. An absence of geometric shapes labelling in (h) indicates no statistical difference between device types for that joint axis of rotation.

The value of the 5^{th} percentile of the total angular range of motion over the course of the kinematic tasks shown in Figure 24, shows a significant difference between texting styles for theabduction/adduction and rotational axis of the CMC joint and the flexion/extension axis of the IP joint. In those cases the slide style has a 20 to 800 percent higher 5^{th} percentile value except in the Abduction/Adduction axis of the CMC joint where it is 60 percent lower. Device type has no significant effect on the 5^{th} percentile value over the duration of the kinematic tasks.

i) j)

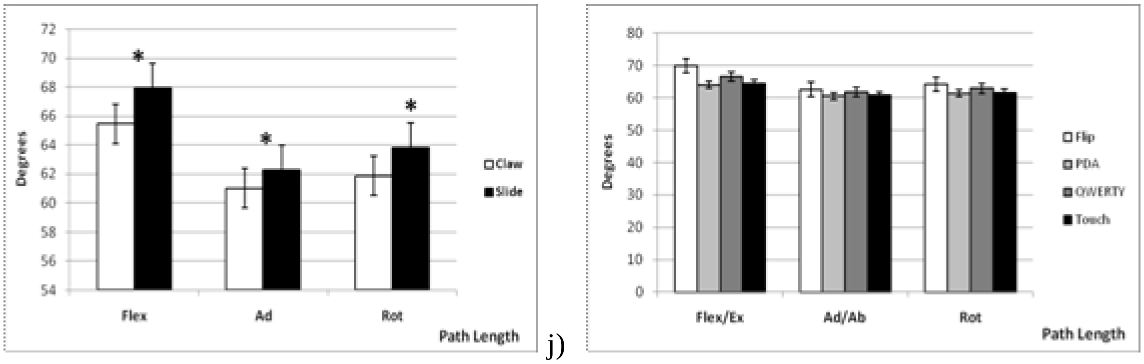


Figure 25: Average values +/- SE for the time normalized path length of the wrist joint angle over kinematic tasks separated by texting style and then by joint axis of rotation in the first chart and by device type and joint axis in the second chart. A star (*) indicates a statistically signficant difference between texting styles or device type for that value and that joint axis of rotation. Different geometric shapes in (j) indicate a statistically significant difference between device types for that joint axis of rotation. An absence of geometric shapes labelling in (j) indicates no statistical difference between device types for that joint axis of rotation.

For the time normalized path length for the wrist joint, shown in Figure 25, there is a significant difference between texting styles for all three rotational axes of the wrist, and in all cases there the value for the slide style is 2 to 3 percent higher, indicating more wrist motion overall. There is no significant effect of device type on the time normalized path length of the wrist in any of the rotational axes.

k) l)

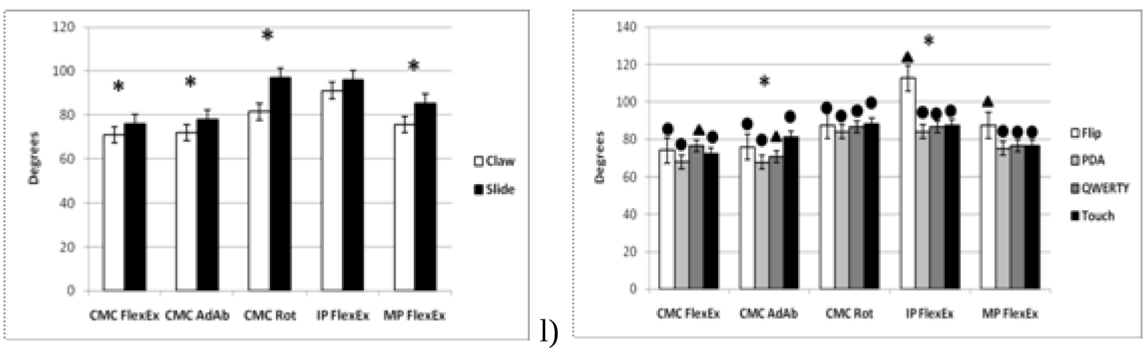


Figure 26: Average values +/- SE for the time normalized path length of the CMC, IP,and MP joint angles over kinematic tasks separated by texting style and then by joint axis of rotation in (k) and by device type and joint axis in (l). A star (*) indicates a statistically signficant difference between texting styles or where device type is a statistically significant factor for that value and that joint axis of rotation. Different geometric shapes in (l) indicate a statistically significant difference between device types for that joint axis of rotation.

For the time normalized path length for all three rotational axes of the CMC joint, as well as for the flexion/extension axis of the MP and IP joints, shown in Figure 26, there is a significant difference between texting styles for all three rotational axes of the CMC joint and for the flexion/extension axis of the MP joint, and in these cases there the value for the slide style is 8 to 4 percent higher, indicating more joint motion overall. There is a significant effect of device type on the time normalized path length for the abduction/adduction axis of the CMC joint and for the flexion extension axis of the IP joint. On average there is 30 percent more motion in the IP joint when using the flip phone than when using the other devices.

Results show that there is an overall significant kinematic difference between texting styles ($P<0.0001$). However, there is not a significant difference for every kinematic variable. There does not appear to be a consistant pattern as to which variables and which joints show significant differences, other than that none of the variables for MP flexion/extension axis are statistically significant. Results also show that there is no significant effect of device type on any of the variables for any of the joints.

4.7 Clustering Algorithm

The variables used as input to the algorithm are the mean joint angle for dynamic trial for a given device, the total angular range of motion for that trial and the 95^{th} and 5^{th} percentile of the total joint angle range of motion over the course of the trial. These variables, which are included in the algorithm are calculated for all three rotational axes of the CMC joint, as well as for the flexion/extension axis of the MP and IP joints and are displayed in Appendix C. Average values for each typing style is summarized in tables 8A and 8B. In addition to this, the time normalized path length for all three rotational axes of the wrist is included in the algorithm as a measure of the amount of hand motion.

Note that each trial indicated in Figure 27 represents a single device type for a given subject. Thus, each participant in the study is represented by four data points.

		CMC			IP	MP
Variable	**Style**	**Flexion/Extension**	**Abduction/Adduction**	**Rotation**	**Flexion/Extension**	**Flexion/Extension**
Mean	Claw	13.487	-19.682	82.437	41.291	29.128
	Slide	14.632	-25.081	92.118	48.120	28.596
ROM	Claw	17.642	17.273	26.883	36.529	24.614
	Slide	24.642	21.205	40.490	38.391	29.487
95th Percentile	Claw	22.363	-11.858	93.805	55.828	37.818
	Slide	29.674	-13.544	90.973	203.802	36.349
5th Percentile	Claw	3.427	-27.345	70.557	20.808	18.035
	Slide	4.880	-33.205	56.380	34.378	14.926

Table 8A: Mean, ROM, 95^{th} and 5^{th} Percentile kinematic summary variables for CMC, IP, and MP joint angles

		Wrist			CMC			IP	MP
Variable	**Style**	**Flexion/Extension**	**Abduction/Adduction**	**Rotation**	**Flexion/Extension**	**Abduction/Adduction**	**Rotation**	**Flexion/Extension**	**Flexion/Extension**
Path Length	Claw	1.091	1.017	1.031	1.183	1.197	1.358	1.519	1.261
	Slide	1.132	1.038	1.064	1.268	1.299	1.614	1.598	1.421

Table 8B: 5^{th} Path Length kinematic summary variables for CMC, IP, MP, and wrist joint angles

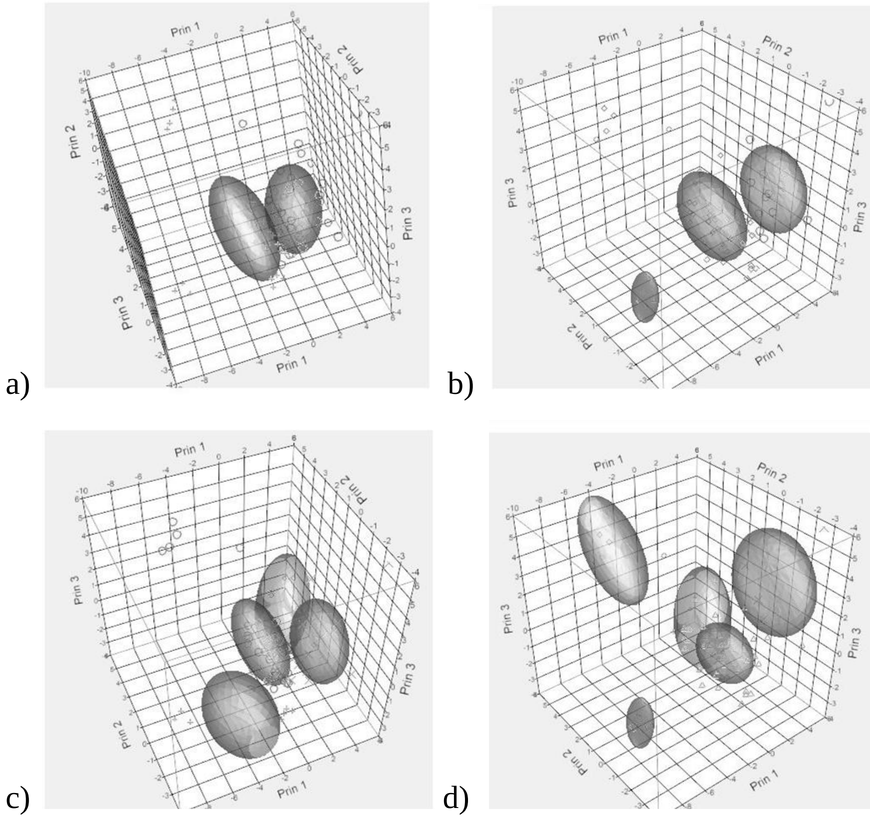


Figure 27: Graphical representation of cluster sectioning of all cases for a) 2 clusters b) 3 clusters c) 4 clusters and d) 5 clusters.

Cluster	Number of Cases in a Given Cluster			
	2 Clusters	**3 Clusters**	**4 Clusters**	**5 Clusters**
1	42	13	43	3
2	30	3	7	6
3		56	6	5
4			16	5
5				53

Table 9: Distribution of cases for different numbers of clusters. Each case represents the summary kinematic data for the use of single device type for a single subject.

Number of Clusters	Max Distance From Mean for Any Variable Over all Clusters
2	10.01
3	9.81
4	8.29
5	8.09

Table 10: Maximum distance from the cluster mean for any kinematic variable, over all cases, and over all clusters

The results of the clustering algorithm show that increasing the number of clusters beyond 2 decreases the variability within each cluster, indicated by the max distance from the mean shown in table 15. However, increasing the number of clusters beyond 2 clusters drastically reduces the evenness of the distribution of subjects between the clusters. At 2 clusters, division of subjects reasonably even, showing a 72% agreement with the human observers. It should also be noted that 2 of the cases where the algorithm did not agree with the human observers were also cases that the two observers had an initial disagreement about and had to come to a consensus. Higher numbers of clusters results in one large cluster of subjects, surrounded by several smaller clusters of 3 to 5 subjects, which suggests that at this level it may be sensitive to small details of performance.

Chapter 5: Discussion

There is an overall significant kinematic difference between texting styles ($P<0.0001$). However, there is not a significant difference for every kinematic variable. There is no consistant pattern as to which variables for which joints are significantly different, other than that there are no statistically significant differences between texting styles for any of the variables for MP flexion/extension axis. In general, the slide style has a higher mean angle, 95th percentile angle, and 5th percentile angle which means that those participants using the slide style have a lower level of flexion in the IP and CMC joints, which confirms that part of the definition of the texting style. The slide style also has a higher time normalized path length for three axes of the wrist joint which means that there is more forearm rotation and hand motion in for those participants using the slide style, which confirms the other half of the style definition. Results show that there is no significant effect of device type on any of the variables for any of the joints, with the exception of the path length for IP flexion/extension, and for CMC abduction/ adduction which showed that more motion was required in these axis for tasks when using the flip phone. This means that in most cases the device used is not influencing the assignment of a style to a participant when using the clustering algorithm. It may also suggest, that at least in the case of the devices examined here, the device type does not influence the texting style used by the participants. However, it also suggests that device type does affect the amount of motion in the flexion/extension and abduction/adduction axes of the thumb. This is likely influenced by keyboard size and key spacing, with more motion required to move between keys that are farther apart, namely with regards to the flip phone.

Results show that there is a significant gender effect for dynamic and static RPE, however it is unclear whether this is a result of gender or style differences, since the slide style group is largely comprised of females and the claw style is largely comprised of males. It could be that females, having smaller hands, and thus shorter thumbs are more inclined to use the slide style naturally because they have more difficulty achieving the required operational range of motion comfortably through thumb motion alone. Without a larger sample of each gender within each style group, it is impossible to tell with any certainty how dependant gender and style are on each other, however future studies with larger sample sizes could examine this relationship in the future.

The most difficult tasks are those requiring the greatest amount of flexion, namely the diagonal motion, which requires 25 to 100 percent more effort than the other tasks, and static holds in the bottom right corner of the keyboard which requires 2 to 56 percent more effort. This may explain why there seems to be an increase in the required effort for dynamic tasks with a greater thumb length. Participants with longer thumbs would have to maintain a greater level of flexion to perform the tasks. This agrees with findings in the literature such as Karlson et al. in 2008, Jonnsson et al. in 2007, and Park and Han in

2010 which show that tasks requiring greater flexion requires greater effort, although none of these studies took thumb length into account. In most cases the horizontal motion is the easiest task, the exception being the device with the full QWERTY keyboard, with which the vertical motion was the easiest. The flip phone which requires the greatest degree of flexion and the highest key press force was the most difficult to use overall. Use of the flip phone resulted in 42 to 53 percent more discomfort than the touch screen phone for static tasks, and 66 to 350 percent more discomfort than the touch screen phone for dynamic tasks. This could be partly due to the fact that the participants had to hold the flip phone with one hand as opposed to two hands, this would likely increase discomfort in the shoulders and neck as well. However, the number of keys pressed was equalized between one and two hand devices, and in all cases only the right hand was used. The average RPE for this device is close to 5, which is quite high for sustained use and could quickly result in fatigue at these levels (Crenshaw 2009). In fact most of the tasks for the PDA and QWERTY devices are also quite high with RPEs of 3 to 4. The touch screen phone, which had the lowest required key-press force also required the lowest effort in both dynamic tasks and static holds. The RPEs for the touch screen phone are relatively low at 2 or lower, which according to some studies is a level of effort that can be sustained for an hour or more without fatiguing (Crenshaw, 2009). When looking at the results for typing speed we see a mirror image of the results for the rating of perceived effort. The motion vectors, and devices which required the least effort, namely the horizontal or vertical motion and the touch screen phone resulted in the highest typing speed. Likewise, those motion vectors and device requiring the greatest effort, namely the diagonal motion and flip phone required in the lowest typing speeds.

Because real phones were used to maximise external validity of the study, the devices differed on multiple characteristics. The most important characteristics may be size/shape and key depression force. There appears to be some relationship between key press force and required effort, most notably with regards to the static holds. Results show that the only statistically significant difference between devices is between the touch screen phone and the other devices. Since the analysis of the kinematic summary variables shows that the device type has not statistically significant effect on the joint angles, this would suggest that the main factor influencing effort is the key press force. The touch screen phone may therefore represent the effort just to hold he thumb in position. This would agree with the results shown in (Crenshaw, 2009) in subjects rated an RPE of 1.5 to 2 for holding their fingers in a static position. It is also interesting to note that in the case of this study, participants were able to hold this position for an hour, without fatiguing, so muscular effort may not be a concern at these levels. With regards to dynamic tasks it is unknown which one of these effects has more of an impact.

With regards to the touch screen phone it should be noted however that despite low ratings in physical effort, there were numerous complaints from the participants during the trials about the difficulties in hitting the correct keys when using the touch screen phone. Given the number of studies demonstrating the connection between tactile feedback and typing accuracy this is not unexpected (Rabin and Gordon, 2003). However this does raise questions about the relative importance of physical effort, when compared to other considerations. A study by Park and Han in 2010 suggested that in lieu of tactile feedback, a greater visual feedback is required, and in cases where the buttons on a touch screen phone are made too small, or spaced too closely together, this can significantly decrease performance and accuracy. Because only trials with 100% accuracy were retained, this study did not address the effect of device on accuracy. Another concern with the use of touch screen phones is that when a film of dirt and oil builds up on the touch screen in interferes with the connection between the thumb and screen, and as a result, the users may press the screen with a far greater force than is strictly necessary, if they find that the keys are not engaging. For the purposes of this study the screen was kept clean, and a zero required key-press force was assumed simply because there is no reliable way to determine what an appropriate cutoff for the key-press force would be under conditions where the keys were not engaging. Finally, participants were moving between only 4 predetermined keys so these motions may not represent typing actual text.

Texting style does have a significant impact on the required effort for dynamic tasks, and has no effect on static tasks. Analysis confirms that there is a significant difference between styles that that the slide style requires on average 20 to 43 percent less effort than the claw style. Surprisingly it does not seem to have any discernable effect on typing speed. This is encouraging because it suggests that an individual could adopt the slide style to decrease the required effort without sacrificing performance. Future studies should examine if an individual can be trained to use the slide style and if this can reduce the loading on the thumb and improve performance. This could help relieve the discomfort at the base of the thumb reported by users in epidemiological studies (Berolo, Wells, and Amick, 2010). However, users in that study also reported pain in the shoulders, neck, and back, conditions that likely would not be relieved by an alteration in texting style. Other interventions would still be required in order to alleviate these issues and further studies would have to be performed in order to determine what these interventions may be. Some possibilities may be investigating the effect of different postures, holding the device at different heights, and typing while standing versus sitting.

As expected, the difficulty of a static hold increases with increased flexion of the thumb, and with any level of key press force, when compared to the touch screen with requires none. However the post hoc tests would seem to suggest that only flexion, and not abduction or rotation is a significant factor in the difficulty of a static hold.

The results of the clustering algorithm show that increasing the number of clusters beyond 2 decreases the variability within each cluster, indicated by the max distance from the mean. However, practically, there is not real improvement from having more than two clusters. Increasing the number of clusters only peels off the users with outlier variables, leaving one ever growing cluster that holds the majority of the users. When using two clusters, there is not complete agreement between the algorithm, and the human observers with regards to which texting style category to assign a participant to. Results show a 72% agreement between the two methods, which is still quite good. It should be noted that 2 of the cases where the algorithm did not agree with the human observers were also cases that the two observers had an initial disagreement about and had to come to a consensus. There are many possible sources for the discrepancy between the two methods such as random error or measurement error that is not present in the human observation. It is also possible that there are other important variable that are not accounted for in the algorithm, but were picked up by the human observers.

The limitations of this study are that only four devices, out of possible thousands of models are used. Each device has a unique combination of key spacing, key size, casing size and shape, weight and tactile feedback. However, the four devices chosen represent examples of main classes of devices currently commercially available. A second limitation is that the measure of effort is a subjective rating by participants, rather than an objective measure, such as EMG. However since RPE is a measure of general discomfort and exertion and it can be influenced by passive elements such as swelling, stiffness and friction in the joints that can cause discomfort but do not necessarily reflected in the electromyogram. This makes RPE a valuable measure even if specific muscles are monitored by EMG.

Furthermore, in order to use EMG, intramuscular EMG would have been necessary, and would have necessitated a much smaller sample size. This would have significantly reduced the power of the statistical comparisons of texting style and device types. In addition, the encumbrance of the EMG leads in the palm may have also altered the natural motion patterns of the subjects and their keystroke speeds. It should also be noted that EMG can charge dramatically with a change of muscle length (Long, 1970), which makes it better suited for tasks involving isometric contractions, than dynamic trials such as those examined in this study.

However, it would still be beneficial to perform future studies with EMG to see if an objective measurement of effort in specific muscles yields similar conclusions. Even if IEMG were only used to record an on/off condition for the muscles of interest, it would also allow us to examine how muscle activation and force sharing changes when different typing styles are used.

This thesis represents the first attempt to identify different text messaging techniques and to examine the effect of using a given technique on typing performance and effort. It is also one of the first to use measures of performance and comfort to compare different classes of hand-held mobile devices. Results suggest that the use of a touch screen device should improve performance and decrease the overall discomfort. There are concerns regarding what effect the absence of tactile feedback will have on accuracy in regular typing situations, but in the conditions examined in this study, the touch screen trial resulted in the fastest typing speed, despite being the device that the users were the least familiar with, so this may not be a major concern. Results also suggest that adopting the slide style will result in a lower muscular effort without sacrificing performance.

The question then becomes whether or not an individual can adopt this new style if it is not their natural style. Future studies should attempt to train individuals in the slide style and investigate the effects of this change on effort and performance. This could help relieve the discomfort at the base of the thumb reported by heavy users in epidemiological studies. However, reported pain in the shoulders, neck, and back, conditions would likely not be relieved by an alteration in texting style. Other interventions would still be required in order to alleviate these issues and further studies would have to be performed in order to determine what these interventions may be.

Technology is changing rapidly and the relationships observed in this study may change with the use of different mobile hand held devices and the adoption of different modes of usage.

Summary

The natural texting style for 20 participants was identified and participants performed static and dynamic tasks on 4 different types of mobile hand-held devices. Participants rated the discomfort in performing a task on a visual analog scale of 0 to 10. For dynamic tasks, keystroke speed and a time history of angles of each joint of the thumb was determined via motion capture. Results showed that for the dynamic condition the tasks which required the most motion in the flexion/extension axis of the thumb also required the most effort, and that there is an inverse relationship between effort and typing speed, namely that those tasks, or devices which required the highest effort resulted in the lowest typing speeds, and visa-versa. Similarly, results showed that those static tasks which required the most thumb flexion also required the most effort. Thumb MP and IP joints were both near 100% of the max ROM for static holds in the bottom right corner of the keyboard. There was also an observed relationship between thumb length and discomfort, where users with longer thumbs experienced more discomfort when performing the typing tasks. This thumb length relationship may account for the observed gender differences in the reporting of discomfort.

Overall, use of the touch screen phone required the least effort for dynamic and static tasks, and also resulted in the highest typing speeds. Therefore it could be beneficial for users who are experiencing discomfort in the thumb from excessive use of handheld mobile devices to switch to using a device with a touch screen interface. This could be a result of having the lowest force required to engage the keys, namely a force of 0 N when the device is used properly since it is activated by a change in surface capacitance. The required force to activate the device may increase dramatically in cases where a film of dirt and oil has built up on the screen, resulting in an interference of the interface between the screen and thumb. This would likely negate the benefits of using a touch screen device. However this situation can be avoided by cleaning the screen regularly. The device which resulted in the lowest typing speed and highest required effort was the flip phone, which also had the highest required force to engage the keys and the greatest key spacing. In addition to this, the flip phone is the only one of the devices examined which is operated one-handed, and this would likely increase the required effort to use, and would likely increase discomfort in the shoulders and neck as well.

Those subjects who used the texting style indentified as the slide style reported significantly less effort for all tasks than those who used the claw style. However, texting style had no significant effect on typing speed, indicating that someone could adopt this style to reduce muscular effort without sacrificing performance.

The next step in this research would be to attempt to train users who use the claw style to instead use the slide style, and examine whether adopting this new motion pattern can reduce discomfort in the base of the thumb resulting from thumb typing.

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APPENDIX A
Use of Handheld Devices Survey
Taken from Berolo et al 2010

Your Use of Computing and Communication Devices

The following questions ask about the time you spent using mobile hand held devices, phones, computers, and gaming devices during a typical day in the last week. A typical day refers to both time at work and time away from work, at home or with friends.

Mobile Hand Held Device Use

1. Do you use a mobile hand held device, i.e. a cell phone, personal digital assistant (PDA) or gaming device? If no, please proceed to question 4.

   Yes ☐ No ☐

2. On a typical day last week, how much time did you spend performing the following tasks with a mobile hand held device?

	Hours	Minutes
a. Emailing, texting, and instant messaging		
b. Scheduling (calendar, appointments)		
c. Internet browsing		
d. Making phone calls and talking on the phone		
e. Listening to music, watching videos, and taking pictures		
f. Gaming: using mobile phone, PDA, or hand-held video game		

3. On a typical day last week, about how much time did you spend using both thumbs to type when using a mobile hand held device?

   a. All (100%) ☐ b. Most (75%) ☐ c. Half (50%) ☐ d. Some (25%) ☐ e. None ☐

Keyboards, Mice and Game Controller Use

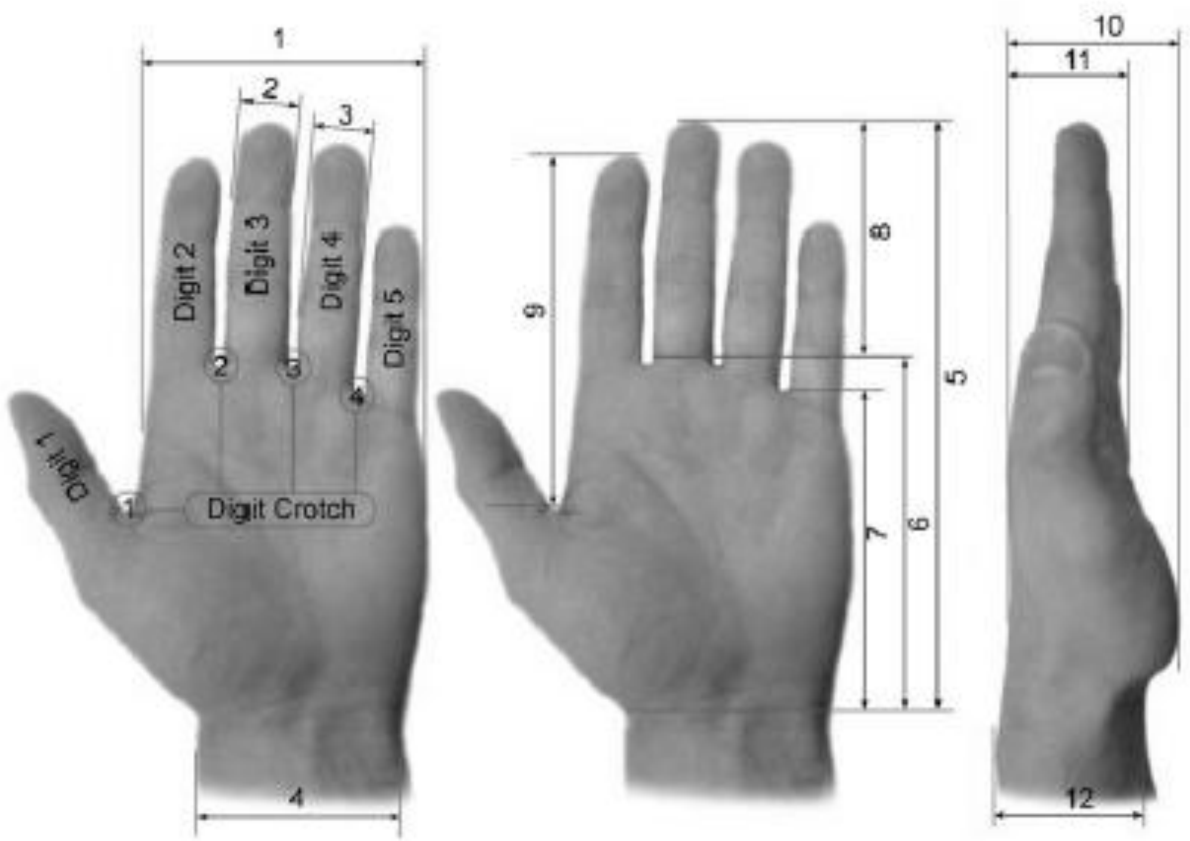
4. On a typical day last week, how much time did you spend:

	Hours	Minutes
a. Using a computer/laptop keyboard and mouse?		
b. Using a Wii Nintendo system game controller?		
c. Using another game controller (e.g. Xbox, Playstation)?		

APPENDIX B
Hand Measurements

Participant Information

Weight	
Height	
Age	



Hand Dimensions

Palm Circumference (mm)	
Palm Length (mm)	
Hand Thickness at MCP (11) (mm)	
Hand Length (5) (mm)	
Hand Girth (mm)	
Thumb Length (mm)	

Active Range of Motion:

Circumduction (deg)	
Extension (deg)	
IP Flexion (deg)	
MP Flexion (deg)	
CMC Flexion (deg)	
Abduction (deg)	
Opposition (deg)	

APPENDIX C
Calculated Kinematic Summary Variables

Mean Angle					ROM					95th Percentile				
CMC			IP	MP	CMC			IP	MP	CMC			IP	MP
Flexion/Extension	Abduction/Adduction	Rotation	Flexion/Extension	Flexion/Extension	Flexion/Extension	Abduction/Adduction	Rotation	Flexion/Extension	Flexion/Extension	Flexion/Extension	Abduction/Adduction	Rotation	Flexion/Extension	Flexion/Extension
1.877252968	-23.6888805	80.37515407	55.0334416	21.16526987	18.4448931	7.743387267	24.03531923	18.50112571	10.36434383	14.32396744	-21.52763148	92.03554205	60.63593866	25.047001
1.515440139	-27.74987445	76.91304427	50.2463881	21.97980973	15.35577623	11.71650805	12.35803061	33.03552858	9.330379559	11.18891037	-20.87238092	82.80217575	56.85216262	24.616988
2.322854349	-23.03036412	80.81488519	52.32234308	22.86440426	9.566270472	9.443248901	18.12788485	20.80405957	9.428133807	8.685508855	-19.43817576	88.34385045	57.56500653	25.946178
5.775944317	-27.37920872	77.66846344	50.89318796	24.26728478	14.20366688	16.29612518	16.96880942	21.192323	13.50585066	13.10613287	-20.84080128	83.33100094	58.08603202	27.827141
9.138659026	-18.37776512	83.39232308	51.40129416	25.87259951	32.63234813	29.95936948	43.609717	27.84480387	41.99614543	29.89841473	-3.893650182	103.1328767	61.01355224	39.086625
0	0	0	32.98732157	0	0	0	0	97.56110283	0	0	0	0	55.62882212	0
0	0	0	57.91082333	0	0	0	0	52.57066808	0	0	0	0	76.05408352	0
0	0	0	51.68508768	0	0	0	0	35.97113005	0	0	0	0	64.58161516	0
6.440772673	-15.30789449	96.67994096	52.08286301	11.84837634	6.964125907	9.325567258	14.49885959	23.44121386	13.60940535	8.456495686	-12.34349423	101.3586401	58.59472564	22.458826
3.282114112	-15.63737974	96.54015112	56.75744278	26.29200505	13.61703025	8.373885943	17.18506572	24.93790326	22.87896696	11.61571553	-11.57299898	102.5049752	64.75729992	38.787426
1.512714456	-16.22111377	100.7891249	51.2104019	24.79837309	9.356616684	7.182522012	29.74747319	29.00769836	20.71362725	11.33734963	-12.95679717	111.1376931	63.09405601	34.675620
10.25435045	-14.81205712	97.02234423	50.93315292	16.36874757	10.7733679	16.0892349	12.77651195	20.09322149	16.24131347	13.7850514	-9.80993141	100.4207157	61.06019788	28.560512
25.53675664	-7.56399083	103.1942801	0	33.41622069	17.43635768	14.02284774	70.93494359	0	28.13157991	30.63029548	1.501350666	112.898101	0	44.255516
21.52502773	-17.30556064	92.65129769	29.40305195	35.93035695	51.13250031	15.87406119	28.95683824	34.31546136	34.3523525	35.68898146	-2.454984327	120.2130067	62.4008588	47.233585
12.2331944	-11.88911777	86.64430694	0	33.88034093	25.14794519	22.72351425	72.52529873	0	26.81005537	32.14625626	-1.215627439	111.4662659	0	46.742069
27.1069936	-14.55569329	109.147473	24.68774166	39.65953468	16.62673093	48.88662675	67.26093871	70.48671207	42.94885311	33.69152072	2.710304815	131.155712	59.466728	52.865801
9.786618	-41.81041709	82.31090582	52.14902353	38.95536636	42.73113865	20.35249655	40.68629786	104.5866847	34.8462476	34.37422345	-32.88749043	103.9135894	96.63207775	59.246324
9.725976065	-34.19141542	80.00316105	43.45035824	35.33952556	29.617913	19.68406674	30.58456178	131.158311	52.50022783	24.42192045	-27.46972235	92.10104996	67.82440305	49.057899
15.78003315	-29.12588065	89.76116638	25.98790351	38.37326765	23.86590203	17.17758414	31.60780601	0.073161033	22.1352358	27.97779504	-20.81588192	103.9313648	62.93494679	42.742068
16.84766991	-41.13093483	88.10738746	32.85009287	46.80152932	24.49673622	23.22428577	21.61888338	114.9602693	38.70566095	33.72868029	-28.31608955	106.1089698	64.02545885	62.103153
15.85480439	-17.7066713	99.07324651	40.77936086	34.10558314	7.072624635	7.115747423	27.70365286	31.79670926	23.02400137	19.16895277	-9.634507799	104.513087	56.46456487	41.824667
18.61456913	-13.99141955	89.48717344	50.42313295	32.55747049	10.50073286	15.06922089	28.94759902	69.76968573	44.23782496	23.90510366	-8.577172917	98.67009602	70.34989557	44.888401
11.67964286	-12.81562128	84.39385738	48.7878087	26.2647092	26.55942637	54.05958764	64.76145841	82.77530054	134.050134	23.31697909	-8.400509765	99.44916687	62.96209741	43.486484
10.90946966	-19.618818	74.18126755	14.40865613	82.3278307	20.84398573	43.62160129	54.43507639	0.040563186	0.231768953	23.69542098	2.064821125	105.6109859	54.22717702	82.330544
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33.77635773	-22.64172092	79.26624348	28.09742822	25.13817514	10.71930344	11.96030243	15.89126795	32.45253638	33.74698409	36.92970993	-14.42382411	88.37307793	49.44928569	40.061991
35.24622082	-19.91371209	81.1439478	44.10633098	28.33079488	7.597175284	16.14359296	11.16444248	26.31434468	22.64611732	38.10774063	-13.83140293	87.42829446	53.98837546	38.372935
27.98326769	-22.21562894	81.02939943	45.61263207	16.34491234	15.53394158	23.75214758	21.37347388	30.4196869	37.40383002	36.89130247	-14.04237362	90.0667403	57.83408575	36.612639
3.228491579	-23.70000111	93.94893616	47.03244315	27.70747601	17.72978168	11.53625259	17.86187971	24.00850679	16.61162316	15.97850434	-18.09643096	107.3422522	55.39541869	31.728369
5.801493335	-17.57009746	97.51557026	42.60000264	28.05763132	18.63404311	18.0253838	23.40001518	22.21090046	21.33578826	14.32160573	-10.41284275	109.1134564	54.21789542	34.730402
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5.321312528	-12.16547112	84.64395416	32.02132572	35.07256326	13.84533828	18.6714027	34.75994929	34.78552946	18.125389	11.4264646	-5.399291374	96.49594872	41.23614344	42.121636
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7.983904616	-24.33544185	87.41750553	60.70587071	14.1895054	13.09840153	17.57892718	18.32540923	21.05042015	19.53319718	17.77004815	-12.70156831	101.2498364	70.65444971	24.253130
35.86253311	-25.48411172	111.5962388	26.32296645	25.33278624	11.67476471	16.56471632	9.127242539	17.14232632	27.27028367	38.95481872	-17.26235428	114.2287883	38.76932565	35.444949
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14.40925467	-28.14668978	71.68246546	46.37670642	41.17964038	20.9328337	21.23895224	31.31009632	23.08997853	29.24627965	27.67785642	-20.38798151	90.17696383	58.24346172	49.378459
13.48728015	**-19.68227514**	**82.43720636**	**41.29143745**	**29.12846387**	**17.64154567**	**17.27274319**	**26.8834381**	**36.52933226**	**24.61365792**	**22.36290309**	**-11.85774917**	**93.80463863**	**55.82830923**	**37.817830**
10.09931102	**8.714956605**	**23.49369326**	**13.84345949**	**13.65821821**	**9.926537049**	**10.54133565**	**16.98110547**	**29.00391279**	**19.95692314**	**10.77620341**	**8.515832175**	**26.45537592**	**15.26509611**	**15.046982**
8.619121466	-36.74425388	92.4234507	65.43805675	33.53599438	29.57191109	29.64291783	82.76393638	18.30443281	33.28976536	24.19840023	-27.12736752	101.1136016	70.77673023	47.374854
6.107383654	-36.85865439	72.33834089	70.42660467	42.67776634	41.00621815	28.60824832	93.1838292	20.20405672	45.49843572	20.85432126	-3.356521428	117.782591	77.14207491	54.512329
9.834825285	-41.24022136	88.24129069	70.40390702	47.0942331	33.39005952	17.43476025	23.82736859	14.30227922	28.8380417	17.88110912	-34.84632199	92.05081096	76.45082952	56.676091
-11.93435346	-61.78784046	56.06016186	74.91825071	66.55604362	60.84962257	41.97988797	87.77724638	33.46205505	66.49511865	16.17383608	-25.75205743	93.13915482	80.01674297	69.26904
11.70520452	-32.93359747	90.31193979	39.20466538	32.41366133	26.68078991	21.09996663	26.24559662	32.99827891	25.24056857	28.30966957	-25.19824967	105.5718765	53.47226452	40.782860
8.89472453	-34.73738711	78.7468093	33.65770994	29.87126501	29.43750875	22.87632063	32.04092848	68.65637388	53.54344631	30.42383672	-25.07278103	104.086981	59.52987008	44.650071
18.84104858	-32.95581276	86.98876773	57.43767493	44.89266742	25.85072897	19.22075803	26.4609043	20.02742514	19.85610514	33.14820979	-24.48397183	110.7638264	63.87488715	52.243049
19.92648105	-34.46936665	85.67509079	55.74307459	44.56363949	29.82994378	23.27403669	34.62654061	24.55688493	20.56184093	34.41276083	-18.84778318	107.6053087	63.32277828	51.538078
14.80443449	-21.55633348	92.93967113	41.76802073	29.10173238	25.11580491	17.10114087	23.39732524	52.06944734	27.38917213	24.66420871	-17.27672178	102.8912072	56.55914256	42.249213
22.45951108	-18.19226805	107.0451932	32.16411735	40.5880689	20.95606612	22.46604147	43.42489172	51.29651831	49.70233414	30.53536972	-6.712674102	121.3032886	54.60986773	53.175921
22.132004	-4.834096542	92.04898301	47.66389741	19.62209213	34.36939409	27.58159549	123.6607488	62.99995583	75.77921895	28.76237532	5.455103062	114.1983015	68.50218017	41.979971
25.28913992	-11.65305993	98.99644887	40.56884676	33.29129107	19.50329842	18.52768415	49.75289422	35.9843535	17.97886499	28.55917002	-4.861702473	107.8577237	58.28336665	38.555851
2.515890016	-33.20293014	80.9004351	56.4112451	29.31174264	30.39363892	11.41180962	34.65220948	27.17310189	13.25811573	22.76618604	-24.18369713	101.5378028	66.19189185	33.022332
8.8595418	-17.66290553	91.87452827	56.20372446	32.02151126	20.42114668	22.61473113	29.29824535	48.61599161	12.26566054	21.97135867	-5.284443182	109.199164	69.2879068	35.083853
27.63612658	-18.37063755	95.25917027	60.05883052	26.88834349	10.36772203	16.35428395	14.47421902	16.82854268	6.733366719	30.04292628	-10.64980087	105.1468619	67.08711617	29.967725
10.533512	-22.55762077	83.7671278	48.77680563	28.65565361	22.06120378	27.09640211	32.06340948	20.63066467	8.201706447	25.26185566	-8.433992199	104.4829554	59.35470715	32.766792
12.91328401	-10.50896072	104.3150969	47.30921349	7.47938775	20.88475087	21.52299602	37.53494539	58.51348755	32.26611416	62.78610784	-0.595636236	17.56671505	949.15	6.716262
22.66074229	-6.014775599	113.5242255	33.53457689	1.850908186	20.11655094	19.86386156	22.58845107	54.6436648	29.50444892	44.95412052	4.154635317	18.68702378	949.15	7.701672
22.0950676	-5.191768993	112.2218092	35.52799837	5.434290646	18.03979228	17.94988101	36.28236765	34.1982923	26.42010513	43.1284449	6.450030856	16.86493043	949.15	3.899575
24.01221894	-15.27721749	107.9146908	42.55995288	16.1025876	12.07793465	24.31017902	29.53784808	116.0017143	35.47985113	55.18456874	7.249167343	18.14225877	807.6	19.025711
4.598145657	-32.14409011	83.04659962	38.80436252	19.31214718	26.04850466	10.49469339	35.36397048	18.3642276	17.217102	19.74939295	-29.65982536	96.73673684	49.46418165	25.871354
19.49393494	-24.35231363	97.63362963	34.67385622	12.02378213	11.65352128	17.3701532	20.85582352	39.83033754	24.94075659	22.41158907	-18.97882094	105.7876492	47.9250641	22.852573
21.95688721	-16.10808177	105.6732845	33.92654864	22.04087419	9.234214487	10.39707674	10.54359806	24.1205549	21.04875539	24.09447997	-11.62195524	109.2034077	42.95731576	31.33730
17.21970159	-32.58555893	92.8843724	37.70958143	20.96380415	13.5411653	19.72654578	21.40034463	27.59561293	16.1868411	21.90287772	-25.42683292	101.6266821	51.39956002	31.120258
14.63227407	**-25.08082305**	**92.11796325**	**48.1204801**	**28.595562**	**24.64172884**	**21.20524883**	**40.48990178**	**38.3907606**	**29.48732235**	**29.67404899**	**-13.54425916**	**90.97278583**	**203.8024366**	**36.348864**
9.13130293	**13.6184754**	**13.17185139**	**13.27843844**	**14.92039029**	**11.22621491**	**6.839094821**	**27.92371569**	**23.0516192**	**17.57168842**	**11.46843994**	**12.7989436**	**34.07355796**	**325.4717198**	**16.599199**

Subject	Device	Style	5th Percentile					Path Length							
			CMC			IP	MP	Wrist			CMC			IP	MP
			Flexion/Extension	Abduction/Adduction	Rotation	Flexion/Extension	Flexion/Extension	Flexion/Extension	Abduction/Adduction	Rotation	Flexion/Extension	Abduction/Adduction	Rotation	Flexion/Extension	Flexion/Extension
01	QWERTY	claw	-8.432808712	-29.48594262	73.77135118	46.58305813	16.44141164	1.079723479	1.027114395	1.036758304	1.250441246	1.060423113	1.295485	1.278313784	1.101073258
01	Flip Phone	claw	-6.372113922	-32.5180772	65.04270158	32.0961453	15.88359671	1.122077869	1.053584205	1.05665307	1.182905516	1.087098094	1.241914	1.430064325	1.127353483
01	PDA	claw	-5.014108376	-27.54463688	72.29188679	40.32292148	17.72686442	1.077499071	1.045854342	1.032575331	1.095071036	1.048467148	1.175618	1.239222052	1.063985551
01	Touch Screen	claw	-2.926237055	-35.39439225	69.1805004	41.51160911	20.95218387	1.024610681	1.027191269	1.00939093	1.139117887	1.155014931	1.214956	1.201029653	1.068905635
02	QWERTY	claw	-4.150927523	-31.08241528	60.99871348	42.25856082	6.714015285	1.046504446	1.021622646	1.024410912	1.273333499	1.182818488	1.398456	1.362402745	1.305116257
02	Flip Phone	claw	0	0	0	-8.550221387	0	1.107293594	1.017285863	1.056239192	0.998507463	0.998507463	0.998507	2.013856766	0.998507463
02	PDA	claw	0	0	0	-123.612991	0	1.094517741	1.064223109	1.16246342	0.998901099	0.998901099	0.998901	2.098366176	0.998901099
02	Touch Screen	claw	0	0	0	40.87681863	0	1.0245602	1.012354877	1.009253076	0.99864682	0.99864682	0.998647	1.663845683	0.99864682
03	QWERTY	claw	-1.54647865	-22.20012721	86.00790692	41.5489018	5.986478358	1.05415825	1.025139774	1.036849759	1.072245704	1.099758131	1.251036	1.323141829	1.174794025
03	Flip Phone	claw	-4.829711094	-23.86660917	78.47617535	40.99713032	14.51823701	1.05706968	1.019128589	1.032320738	1.17032873	1.130985531	1.441699	1.345673638	1.360647839
03	PDA	claw	-4.339524757	-22.45586033	80.82015388	40.27035361	15.20003021	1.028838472	1.006196346	1.031530414	1.081937033	1.074131764	1.338201	1.26902912	1.16607346
03	Touch Screen	claw	3.933042666	-23.99191152	87.95785746	42.91147458	8.564226412	1.094977017	1.024980798	1.024229177	1.049352633	1.188024783	1.181139	1.236451719	1.195623299
04	QWERTY	claw	15.61576374	-14.01192646	87.47495086	0	17.75438646	1.068248438	1.006303101	1.027272854	1.299875102	1.21483177	1.680545	0.998907104	1.54448823
04	Flip Phone	claw	12.68889308	-24.68860276	78.91880588	-42.98090781	18.72489725	1.1601382	1.009945873	1.049811373	1.40010602	1.373547901	1.614915	2.164497149	1.504736415
04	PDA	claw	5.261068176	-23.74992922	74.99477297	0	19.50176565	0.945901709	0.898751126	0.905304842	1.123193508	1.079220904	1.2493	0.89497307	1.156031604
04	Touch Screen	claw	-3.032179999	-39.31859152	63.95852111	5.047377595	16.38232701	0.945546878	0.892879293	0.899411663	1.237565315	1.577640322	2.175882	1.764641595	1.484271155
05	QWERTY	claw	-9.323848833	-49.96261315	63.30657286	-3.80865881	24.94657982	1.096132101	1.031677816	1.078695329	1.84913998	1.380643582	1.829402	3.186697346	1.768812682
05	Flip Phone	claw	-7.207925858	-45.65992613	65.03862298	-9.350946122	24.56772629	1.293863098	1.053626329	1.155222552	1.562309317	1.359737462	1.653196	3.03986548	1.711003121
05	PDA	claw	4.350698263	-35.63259062	78.39396355	-10.77452778	29.11163898	1.152075127	1.030536638	1.056104835	1.26231996	1.175084654	1.413385	2.37223088	1.21214937
05	Touch Screen	claw	4.269118652	-48.80340517	78.02548311	-15.46267423	28.64248509	1.050657613	1.022572424	1.039002689	1.376824571	1.525836229	1.404491	2.699610188	1.448817851
06	QWERTY	claw	-38.54087551	-31.51838867	28.87790925	27.40231149	-6.004766763	1.105980177	1.029110952	1.083460212	1.212730558	1.128356433	1.578164	1.366228301	1.393032689
06	Flip Phone	claw	5.869367578	-24.7100843	73.89346085	25.75818106	19.68899868	1.068739221	1.014209048	1.051296935	1.13673018	1.154088003	1.588288	1.778801015	1.55821182
06	PDA	claw	5.73003993	-28.68296236	74.33082956	35.05619612	18.86573138	0.868840749	0.836513027	0.857432974	0.944081837	1.011135856	1.175771	1.166749618	1.284894645
06	Touch Screen	claw	4.979545258	-36.25411253	60.01684043	14.409131	32.49517635	0.956944724	0.922430993	0.953278437	1.163576647	1.717048738	1.955332	1.1786274	1.225074754
07	QWERTY	claw	18.12842525	-26.64883865	73.45408405	-3.806909039	10.50803751	1.124650286	1.045366042	1.053902507	1.104022233	1.111899154	1.140277	1.675665931	1.217848961
07	Flip Phone	claw	22.69787918	-30.33233269	70.48159521	14.9756993	9.832098225	1.162759386	1.068479159	1.071598954	1.131707321	1.133922773	1.228855	1.779430933	1.390107638
07	PDA	claw	23.85926123	-26.93644053	76.95918915	27.8569949	14.8663349	1.083170501	1.039846608	1.033360363	1.119752919	1.140541974	1.164299	1.356089359	1.28296738
07	Touch Screen	claw	22.1935722	-32.06490469	73.25672619	30.74127724	3.507288766	1.112142802	1.043704025	1.040119847	1.245285973	1.517538397	1.568654	1.700268526	1.689554282
08	QWERTY	claw	-5.580019443	-28.40745527	85.17993536	38.64365294	18.88991364	1.193795378	1.024095235	1.077087248	1.275657927	1.155696994	1.329715	1.193958011	1.150105114
08	Flip Phone	claw	-3.497052162	-23.82985411	89.00486711	35.89414977	17.03335043	1.349455106	1.026213596	1.100490509	1.252821674	1.302780355	1.428936	1.324596882	1.304857426
08	PDA	claw	-2.384062804	-28.75399166	87.42150427	37.61555722	19.03855155	1.117245451	1.015257399	1.037104906	1.131114109	1.130107138	1.219478	1.172848656	1.118332072
08	Touch Screen	claw	2.682102479	-26.16834757	92.80381564	36.39613805	19.8183207	1.236470138	1.016428111	1.072458006	1.18096097	1.324570357	1.344459	1.192442871	1.198625655
09	QWERTY	claw	3.959290998	-23.82944978	73.51600577	15.10075302	23.53367528	1.086764426	1.045920493	1.037399582	1.066899382	1.102604391	1.394191	1.680911141	1.259887527
09	Flip Phone	claw	-0.267259323	-22.22159382	67.68620465	17.43103992	27.2632244	1.184216907	1.059847978	1.051878763	1.111224936	1.165120004	1.532058	1.528814878	1.219449213
09	PDA	claw	0.208220264	-21.61891763	75.05869679	29.1253266	28.50096126	1.087871646	1.034141985	1.018389868	1.100817076	1.114387057	1.371187	1.457524702	1.185427518
09	Touch Screen	claw	1.766376877	-18.4755378	70.4978945	30.05930659	29.25803123	1.127622915	1.032024114	1.025838617	1.067045006	1.178798356	1.408732	1.369008811	1.122119067
10	QWERTY	claw	10.10039914	-25.87209996	78.12420879	28.66618134	25.26927002	1.102705787	1.023146919	1.019772883	1.210515374	1.12835953	1.259654	1.088665244	1.159574735
10	Flip Phone	claw	5.586214372	-22.72935422	84.66749812	41.81548601	26.35075339	1.02572156	1.010541157	1.008255294	1.199822144	1.201580151	1.19425	1.282384501	1.223359986
10	PDA	claw	4.804646129	-25.76222689	82.50095302	48.54011013	29.41569591	1.017081502	1.00428631	1.003032271	1.181087497	1.248964866	1.225383	1.221002779	1.26699324
10	Touch Screen	claw	3.498357468	-22.89192397	85.95732084	25.57374908	28.29861823	1.016606676	1.005822752	1.012106968	1.126192751	1.252741579	1.21371	1.254044784	1.27275009
11	QWERTY	claw	13.57487583	-30.50100346	84.3560685	37.59252893	10.77059234	1.045110094	1.022392191	1.024397559	1.157191225	1.091067083	1.234925	1.095667584	1.099500339
11	Flip Phone	claw	18.37281723	-31.53128433	85.15395161	29.74195405	4.618188347	1.28352181	1.070989715	1.043756805	1.205146739	1.246808628	1.25186	1.335505899	1.246189778
11	PDA	claw	5.682490962	-32.28189998	79.30140229	47.86050642	8.101691781	1.065422339	1.018501156	1.016764977	1.052675409	1.091263633	1.229214	1.207595606	1.138202247
11	Touch Screen	claw	27.33885328	-32.08529497	102.008914	18.58076851	15.43745572	1.056534348	1.018646447	1.013379926	1.102959221	1.207317389	1.150529	1.186573909	1.20720851
12	QWERTY	claw	7.95995848	-20.16155501	71.76332498	8.12435565	42.4074829	1.05076532	1.013104628	1.018904566	1.144398286	1.133972014	1.221192	1.51755899	1.111895098
12	Flip Phone	claw	11.75293301	-33.88289756	72.22874043	29.8376439	25.06133697	1.115269916	1.025342639	1.012603612	1.181689305	1.249591348	1.384834	1.480699106	1.396852185
12	PDA	claw	-0.960525188	-35.14731035	58.90746104	31.20197641	32.87340247	1.14642599	1.038059398	1.030149723	1.356922553	1.192111296	1.467338	1.445622937	1.216361505
12	Touch Screen	claw	6.025706986	-38.86939874	64.68515109	38.6987615	28.37904139	1.048661485	1.015202642	1.007973532	1.210651959	1.330427909	1.361198	1.280524517	1.201982374
		Mean:	**3.426755406**	**-27.34452123**	**70.55736445**	**20.80783859**	**18.03536057**	**1.090935215**	**1.016887365**	**1.031243673**	**1.183245909**	**1.197335866**	**1.357878**	**1.518763192**	**1.261068843**
		SD:	**10.86071725**	**10.16547394**	**21.62636417**	**29.2946755**	**10.17242506**	**0.087565204**	**0.043702344**	**0.051785089**	**0.149975265**	**0.153006913**	**0.23361**	**0.488686572**	**0.180699716**
13	QWERTY	slide	-4.944342121	-54.42576187	69.96915928	59.34329721	24.89265124	1.06789733	1.017832877	1.014970759	1.351233009	1.468909929	1.780426	1.159769487	1.391901468
13	Flip Phone	slide	-8.030955282	-49.71580462	43.21929257	58.02785195	-5.346543284	1.080344236	1.017566036	1.072490092	1.392874908	1.863720398	1.904534	1.533732089	2.046122557
13	PDA	slide	-7.944362483	-53.98608099	57.71543337	64.69080942	34.62305796	1.02554796	0.982254222	0.991104143	1.186497367	1.19906497	1.377697	1.066663448	1.177112704
13	Touch Screen	slide	-20.68216127	-63.576111	1.577763512	56.46073398	31.42966351	1.056372471	1.021712316	1.105288898	1.688907079	1.609585312	2.306572	1.404175899	1.952063255
14	QWERTY	slide	0.568281423	-44.23204221	74.50403955	27.88773105	19.26471228	1.07819002	1.027107371	1.023307585	1.429465153	1.358705479	1.548513	1.306317478	1.379518597
14	Flip Phone	slide	-2.633531306	-47.07225731	68.27173599	-1.661564	0.242910891	1.253267811	1.072048993	1.026472466	1.501992935	1.426650873	1.753413	4.328779107	2.674695369
14	PDA	slide	4.450332143	-42.30752077	76.04743071	45.6301007	32.32067232	1.06345472	1.019800383	1.011948687	1.316409489	1.25360896	1.450023	1.205084141	1.178309355
14	Touch Screen	slide	6.638107466	-45.39311934	72.06677884	37.04377926	31.8089665	1.128905658	1.042175348	1.026185162	1.599646013	1.706407212	1.80741	1.41176283	1.268974849
15	QWERTY	slide	-0.021754635	-34.59481953	81.80299657	11.22641664	21.32984346	1.327768247	1.035608659	1.107184267	1.365943851	1.280816194	1.548463	1.710742011	1.398120405
15	Flip Phone	slide	13.42410686	-24.44566763	90.1107047	5.584484198	25.6153574	1.229807363	1.030534447	1.117495299	1.268660683	1.375540216	1.722887	3.060444054	1.854756798
15	PDA	slide	13.57046194	-15.37718664	22.94990649	24.58862162	-5.684022699	1.181532924	1.076504344	1.09156985	1.297520248	1.392263774	3.912684	2.331939029	2.788494509
15	Touch Screen	slide	16.66961148	-18.20342997	91.89691392	29.56242425	26.95000731	1.137728858	1.016645702	1.050879521	1.093108499	1.217942679	1.338752	1.622833582	1.124299697
16	QWERTY	slide	-6.031840361	-37.38470673	72.75793064	15.91900931	25.11521457	1.082417869	0.945659529	0.986496395	1.188264928	1.044988547	1.248113	1.171340906	1.01330046
16	Flip Phone	slide	-1.716998037	-25.92333596	78.88180467	30.78784819	23.48054193	1.211966472	1.034204446	1.056331288	1.289700984	1.370804097	1.624249	1.683877005	1.141562519
16	PDA	slide	19.40360363	-27.43411444	88.25682913	38.35204131	21.25047058	0.964022443	0.90475295	0.930832862	0.9453365	1.021256852	1.021452	1.149300032	0.971649783
16	Touch Screen	slide	1.271343331	-29.54477165	74.67773428	33.23458852	24.82982373	1.144808267	1.023361317	1.06098336	1.24992851	1.340944219	1.455518	1.385095316	1.067166665
17	QWERTY	slide	17.26199083	-14.43551244	-9.432973867	51.85	-4.858039212	1.172239933	1.054488374	1.145644756	1.128609217	1.132842037	1.371177	1.480236725	1.292376652
17	Flip Phone	slide	4.693977971	-7.118074365	0.265101141	51.85	1.480743118	1.139389867	1.10027972	1.237354171	1.061286393	1.095853079	1.138523	1.214916324	1.177734732
17	PDA	slide	26.76552583	-1.734213542	1.638247355	51.85	-4.149123563	1.140338438	1.061237832	1.158609452	1.049609169	1.053254967	1.119997	1.199404029	1.152530469
17	Touch Screen	slide	35.52758226	-18.57165148	-13.85284763	44.4	-13.27144304	1.104651031	1.036236445	1.087933399	1.034476978	1.236614818	1.294016	1.438526246	1.24136828
18	QWERTY	slide	-12.24614333	-41.35405722	60.47904878	29.92009298	13.09423086	1.214426049	1.141656672	1.077107234	1.615947594	1.169099027	1.928518	1.365190601	1.172673422
18	Flip Phone	slide	6.41219564	-34.61331615	78.80041796	25.15148761	4.516621356	1.134757359	1.106372984	1.069539152	1.158839565	1.226891754	1.469256	1.472918356	1.306666577
18	PDA	slide	5.236531368	-21.85806713	86.80446654	5.724141802	13.2129556	1.151252291	1.08061601	1.048462182	1.100706038	1.070186904	1.321187	1.348846114	1.154556456
18	Touch Screen	slide	9.468843123	-43.60721228	83.72048059	27.64497374	16.07717689	1.086037117	1.06505579	1.038468922	1.107879984	1.268570523	1.301153	1.290040162	1.185012041
		Mean:	**4.879809601**	**-33.2045348**	**56.38034979**	**34.37786957**	**14.92610207**	**1.132380197**	**1.038071365**	**1.064027496**	**1.267618546**	**1.299355118**	**1.614356**	**1.597580624**	**1.421290317**
		SD:	**12.76197452**	**16.02163249**	**35.11255371**	**18.54046638**	**14.56544108**	**0.079542877**	**0.04978012**	**0.063759776**	**0.198121131**	**0.210659092**	**0.573193**	**0.720683938**	**0.488487461**

APPENDIX D
Matlab GK Clustering Code

```
function [U, V, F] = gk(Z, U0, m, tol, beta, gamma)
%
%Gustaffson Kessel Algorithm
%
%[U, V, F] = gk(Z, U0, m, tol, beta, gamma)
%---------------------------------------------------------
% Input:  Z:                N       by n data matrix
%                           U0:     inital number of clusters
%                           m:      fuzziness exponent (m >1)
%                           tol:    termination tolerance
%                           beta:   condition number threshold
%                           gamma:  weighting for covariance
%---------------------------------------------------------
% Output:       U:                  Fuzzy Partion Matrix
%               V:                  Cluster Means Centre
%               F:                  Cluster Covariance Matrices
%---------------------------------------------------------
%               Input
%---------------------------------------------------------

%create input here

%---------------------------------------------------------
%             Prepare Matrices
%---------------------------------------------------------
[mz,nz] = size(Z);                              % data size
c = size(U0, 2);
if c == 1, c = U0; end;                         % # of clusters
mZ1 = ones(mz,1);
nZ1 = ones(nz,1);
V1c = ones(1,c);
U = zeros(mz,c);                                % partition matrix
d = U;                                          % distance matrix
F = zeros(nz, nz, c);                           % covariance matrix
f0 = eye(nz)*det(cov(Z)).^(1/nz);               % identity matrix
%---------------------------------------------------------
%              Initialize U
%---------------------------------------------------------
if size(U0,2) == 1,
  minZ = V1c'*min(Z);
  maxZ = V1c'*max(Z);
  V = minZ + (maxZ - minZ).*rand(c,nz);
  for j = 1 : c,
         ZV = Z - mZ1*V(j,:);
         d(j,:) = sum((ZV.^2)')';
  end;
  d = (d + 1e - 100).^(-1/(m-1));
  U0 = (d ./ (sum(d')'*V1c));
end;
%---------------------------------------------------------
%               Iterate
%---------------------------------------------------------
while max(max(abs(U0-U))) > tol
  U = U0;
  Um = U.^m;
  sumU = sum(Um);
```

```
  V = (Um'*Z) ./ (nZ1*sumU)';
  for j= 1 : c,
            ZV = Z - mZ1*V(j,:);
            f = (1-gamma)*f + gamma*f0;
            if cond(f) > beta;
                      [ev, ei] = eig(f);
                      eimax = max(diag(ei));
                      ei(beta*ei < eimax) = eimax/beta;
                      f = ev*diag(diag(ei))*inv(ev);
            end;
            d(:,j) = sum((ZV*(det(f)^(1/nz)*inv(f)).*ZV)')';
  end;
  d = (d+1e-100) .^ (-1/(m-1));
  Uo = (d ./ (sum(d')'*V1c));
end;
%-----------------------------------------------------------
%               Create Final F and U
%-----------------------------------------------------------
Um = U0.^m;
sumU = nZ1*sum(Um);
for j = 1 : c,
  ZV = Z - mZ1*V(j,:);
  F(:,:,j) = nZ1*Um(:,j)'.*ZV'*ZV/sumU(1,j);
end;
%------------------------------------------------------------
```