Phuong Nguyen — 100799

A Study of One-handed Interaction of Large Smartphones: GUI Changes for Better Ergonomics

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Department of Computer Science and Media Technology
Gjøvik University College

Avdeling for
informatikk og medieteknikk
Høgskolen i Gjøvik
Postboks 191
2802 Gjøvik

Department of Computer Science
and Media Technology
Gjøvik University College
Box 191
N-2802 Gjøvik
Norway

Abstract

People tend to use their smartphones one-handed, which is unergonomic for the human musculoskeletal system. Stretching the thumb to reach certain touch keys is uncomfortable. Especially now that smartphones have large screens, normally ranging from 4.5” and above. Exaggerated use of smartphones can lead to repetitive strain injury (RSI), which is caused by static, repetitive movements over an extended time.

This master thesis investigates how different touch key locations and touch key sizes affect the ergonomics of user interfaces on large smartphones. Moreover, it examines if the principles of the functional area improve the ergonomics of mobile user interfaces. The functional area is the surface of the touchscreen that is reachable by the thumb. Expert interviews were used to collect data to make hypotheses regarding improving the ergonomics of mobile user interfaces for one-handed interaction. An electromyography (EMG) test was conducted to investigate the hypotheses. EMG is a technology used to measure muscle contractions.

The results show a significant correlation between a user interface that applies the functional area and a decline in muscle contraction. However, the decline in muscle contraction only occurs if the functional area is designed specifically for the user’s dominant hand. There were no significant differences between the touch key sizes and the extent of muscle contraction. The findings from this master thesis support the idea that the functional area and changes in the user interface design affect the ergonomics of smartphone interaction.

Acknowledgements

This master thesis was originally intended only to address the usability of one-handed smartphone interaction. The health related topic was later included because I developed repetitive strain injury (RSI) in both of my hands this winter. There was a lot back and forth for whether I was going to finish the thesis this semester. It has been many challenging months that have come to an end. Today, I still suffer from RSI in my left hand.

I want to give a big thanks to Cristina Marco for being my good supervisor the last two semesters. Thank you very much for all the advice and the useful tips regarding academic writing. Moreover, I want to thank Frode Volden for the optimism, the always good mood, and the good advice and assistant in the data analysis. I also want to thank Miriam Begnum for all the inputs during this semester and, of course, for having been a great contact teacher in three semesters. Lastly, I want to thank Lillehammer University College for the loan of the EMG tools utilized in this study.

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1 Introduction

Multi-touch smartphones have since the first generation of iPhone and Android devices changed the way we interact with mobile phones. If we look back at the early 2000s, that is only 15 years back in time, phones were mainly used for calls and texting. In contrast, we now use our smartphones for a wide variety of tasks, including accessing the Internet, e-mails, music, photos, maps, and games—in addition to the traditional phone functionalities. It has cannibalized the sales of products like point-and-shoot cameras and GPS devices; it even has cut off the sales of PDAs and portable media players. Mobile payment services like Apple Pay, Google Wallet, and Samsung Pay moreover indicate the utilities of smartphones in the future. Smartphones have therefore highly changed in terms of operations and usage frequency (Verkasalo 2009; Oulasvirta et al. 2012), and has even surpassed desktop and laptop computers in online traffic with 60% of the share (Lipsman 2014). Multi-touch smartphones are now powerful pocket computers.

The smartphones released in the last few years have had a significant increase in screen size compared to the older models. The first multi-touch smartphones had displays ranging from 3.0"–3.5". In contrast, smartphones today normally have screen sizes from 4.5" and above. Despite the increase in screen sizes, the current user interfaces have not been changed accordingly. iOS and Android together made up 96% of the smartphone market share in the fourth quarter in 2014 (IDC 2015), meaning that these two mobile OSes nearly make the whole current smartphone market. However, the user interface design and interactions of iOS and Android remain highly similar to the first versions released 7–8 years ago, including frequent touch keys at the upper corners of the screen. Figure 1 shows the clock app in Android 5.0 as an example of touch keys located at the top of the screen. The screenshot is taken from a Google Nexus 5 with a 4.95" screen.

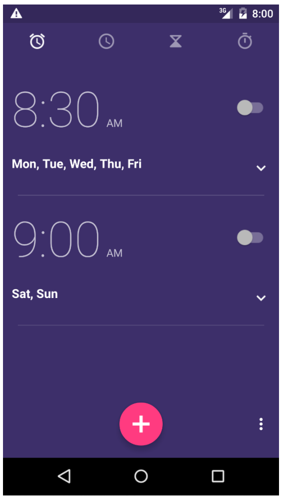

Figure 1: The clock app in Android 5.0.

Even if technology has given us advantages like improved communication, and easy access to information and entertainment, there are also disadvantages. A downside of the widespread of technical devices is the health risks followed by long-term repetitive movements. Computers have in many decades been well known to the development of repetitive strain injury (RSI) caused by keyboard typing (Keller, Corbett&Nichols 1998) and use of computer mouse (Jensen et al. 2002). Heavy use of smartphones can also develop RSI, such as carpal tunnel syndrome (Shim 2012). Carpal tunnel syndrome is a hand and arm injury caused by a compressed nerve. In fact, use of laptops, tablets, and smartphones are all prone to injury and disability caused by bad posture and repetitive movements (Bachynskyi et al. 2015). Thus, as people tend to use several technical devices throughout the day, it is hard to point out one single source of musculoskeletal issues (Stawarz&Benedyk 2013).

RSI is a form of injury caused by physical, repetitive tasks such as computer and smartphone usage over an extended time. RSI includes common symptoms like carpal tunnel syndrome and tendonitis (inflamed tendon), and normally occurs in the wrists, hands, forearms, shoulders, and neck. Occupational related RSI is very common today and has seen big growths in the last few decades. It has costed the society expensive compensation costs. RSI has even reached epidemic proportions in certain industries (Yassi 1997).

When operating mobile devices, most users prefer to interact with one hand (Karlson, Bederson&Contreras-Vidal 2006). It is however challenging as the major mobile OSes are not designed for one-handed interaction. There are certain areas of the screen that cannot be reached by the thumb when interacting one-handed. The areas the thumb can reach, called *the* *functional area* (Bergstrom-Lehtovirta&Oulasvirta 2014), depends on the size of the screen and the user's hand. The larger the screen and the smaller the user's hand, the smaller is the thumb's functional area when operating a mobile device one-handed.

1.1 Project Description

Advancements in mobile technology have made it possible for providers to offer a wide range of different mobile services. The services range from entertainment services, like games and multimedia contents, to utility services, like mobile bank and online dictionaries. A big advantage of mobile devices is the possibility to use it anywhere at any time—an ability that has lead people to use Internet and multimedia services actively on the go (Verkasalo 2009). People on the go—travelers—often operate their mobile devices one-handed, especially while walking, due to an occupied second hand (Karlson, Bederson&Contreras-Vidal 2006). The second hand can, for instance, be carrying a bag. Thus, only one of the hands is available. When interacting a mobile device one-handed, the hand's key muscles are holding the device while the thumb is used for input. The thumb's functional area is restricted, which makes some parts of the screen easier accessible than others. The top corners of a large screen are hard to reach one-handed because it is far away from the thumb. In contrast, areas in the middle of the screen are easily accessible. Figure 2 shows an estimated functional area on an HTC Nexus One, with a 3.7" screen. A 3.7" screen is small compared to the current standards, where most of the screens are from 4.5" and above. The functional area, the green fields, therefore nearly covers the entire screen of the presented device.

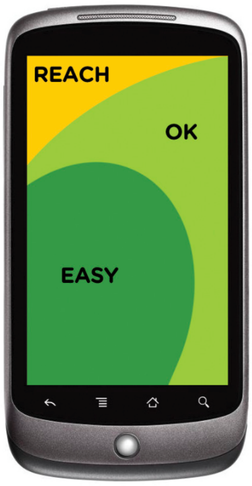

Figure 2: An example of the functional area. Source: Wroblewski (2011, p. 73)

None of the current major mobile OSes take the functional area into account. Both iOS and Android have touch keys spread over the whole screen, leaving many primary functions outside of the functional area. Figure 3 shows an example of how the user interface of the iPhone 6, with its 4.7" screen, is compared to the functional area. The challenge with touch keys outside of the functional area is not only in terms of being hard to reach; touch keys far away from the thumb also are uncomfortable (Wroblewski 2011). Moreover, as touch keys are placed beyond the functional area, the user must adjust the grip to reach it. A second hand may need to be recruited to change the grip. If grip changes are frequently done by the user while paying attention to the surroundings, it can be harmful for the mobile interaction (Bergstrom-Lehtovirta&Oulasvirta 2014).

Designing for iOS

iOS embodies the following themes:

- **Deference.** The UI helps people understand and interact with the content, but never competes with it.
- **Clarity.** Text is legible at every size, icons are precise and lucid, adornments are subtle and appropriate, and a sharpened focus on functionality motivates the design.
- **Depth.** Visual layers and realistic motion impart vitality and heighten people's delight and understanding.

Figure 3: iOS does not apply the principles of the functional area.

Use of technical, portable devices can be harmful to the human musculoskeletal system, whether it is tablets, laptops, tabletops, public displays or smartphones. Smartphone usage affects the lower back, the upper back, as well as the shoulders (Bachynskyi et al. 2015). Use of smartphones can also develop carpal tunnel syndrome, which is a common hand related type of RSI (Shim 2012). Carpal tunnel syndrome alone accounts for a large share of occupational illnesses, comprised over 40% of all RSI disorders related to the upper extremity in 1994 (Jagga, Lehri&Verma 2011). In USA in the 1990, RSI comprised over 60% of all occupational illnesses, with almost 1.9 million workers suffered from carpal tunnel syndrome alone (Yassi 1997). Moreover, all forms of RSI related occupational illnesses cost the society a vast amount of compensation. As RSI increases largely in many countries, and smartphones have become widespread, it is therefore highly relevant that user interfaces of smartphones should be ergonomically designed.

In order to investigate the topics of smartphone usage and the potential musculoskeletal issues provided, this master thesis examines different touch key locations and touch key sizes, and how they affect the muscle contraction during use. Moreover, it addresses the ergonomic effect of the functional area in one-handed interaction. The majority of people prefer to interact with their mobile devices one-handed, often because of practical reasons like while walking with the second hand occupied (Karlson, Bederson&Contreras-Vidal 2006). This study, therefore, examines one-handed interaction specifically. The goals of this study are to inform about the importance of ergonomic user interfaces, and how ergonomics can be affected by the user interface design. The information from this master thesis is aimed at developers, as well as consumers of mobile digital solutions. The data from the study will be used to suggest a new user interface layout with a focus on usability and ergonomics in terms of one-handed interaction.

1.2 Research Questions

This master thesis consists of two research questions, where both focus on one-handed smartphone interaction:

1. Which factors affect the ergonomics of user interfaces on large smartphones?
2. To what extent will a user interface design that takes the functional area into account, improve the ergonomics of large smartphones?

1.3 Explanations of Terms

There are several terms frequently used in this master thesis that are important to understand the study.

Touch key refers to the interactive elements in a GUI.

Touch key location refers to the placement of interactive elements in a GUI.

Touch key size refers to the size of interactive elements in a GUI.

One-handed interaction, or *one-handed smartphone interaction*, refers to operating a smartphone one-handed with the thumb. This term implies thumb interactions on the touchscreen while the remaining fingers are holding the smartphone device.

The functional area is the area of a user interface that is reachable by the input finger—which in this thesis is the thumb—when operating a smartphone one-handed.

RSI is an abbreviation for "repetitive strain injury". This term is used for musculoskeletal issues caused by repetitive movements over an extended time. In this thesis, *RSI* is specifically related to overuse of technical devices, like smartphones, tablets, and computers.

Ergonomics is used for the comfort related to musculoskeletal and physiological aspects.

1.4 Thesis Structure

Chapter 2 presents the background for this master thesis. It reviews the different technical aspects regarding the topic of this study, addresses studies related to mobile interaction, both in terms of usability and health, and presents the pre-study conducted prior to this master thesis. Chapter 3 explains the methodologies behind the research in this master thesis and is divided into two parts: one for each conducted research. The results of the research are presented in Chapter 4. Chapter 5 discusses the results from this master thesis, and also suggests a design guideline for an ergonomic user interface. Chapter 6 presents the conclusion of the study, and, finally, suggests future work to extend the topic started by this master thesis.

2 Background

This chapter presents the background for this master thesis. It starts with a review of the different technical aspects regarding the topic of this study. Moreover, it addresses other studies related to mobile interaction, both in terms of usability and health issues. Lastly, it presents the pre-study and its results conducted in the fall semester 2014, as part of the course *IMT4882 Specialization Course 2.*

2.1 Technical Aspects in This Thesis

2.1.1 Mobile Technology Advancements

In the last few years, the use of smartphones has increased largely due to its technical advancements. First, the broad support of modern web technologies—both the newest front-end and back-end languages—brings the mobile surfing experience to a new level compared to older mobile phones with Internet access. Secondly, design and development techniques like *mobile first approach* and *responsive web design* lead to mobile optimized content. Thirdly, the fact that multi-touch technology is widespread makes mobile devices very flexible in terms of user inputs—virtual keyboards, buttons, and interactive elements adapt the content and its functionalities. These factors make content easily accessible on mobile devices, which has been vital for the popularity of smartphones.

Mobile first is a development technique where mobile devices are prioritized. This development technique means that content gets created on mobile devices before desktop and laptop computers because the majority of online traffic comes from mobile devices (Lipsman 2014). Mobile first is, therefore, an approach that has adapted the current market situation. Many big companies have adopted the mobile first approach, like Google and Facebook (Wroblewski 2011). Mobile first is commonly combined with responsive web design.

Responsive web design (RWD) is a development technique used to adapt websites to various screen sizes, within one set of code and content. The code contains different styles for various screen widths. This approach allows one single website to be appropriately presented on a wide range of devices by applying the specific code for a certain screen width (Gonzalez

2013). RWD allows cheaper and more efficient development of websites to different devices compared to dedicated websites for specific devices.

2.1.2 Multi-touch Technology

Many current consumer products have multi-touch technology, including smartphones, tablets, and laptops. Multi-touch is a term used to describe a surface that can register two or more contact points simultaneously. Some devices also register different pressure levels, like the Apple Watch. Unlike single-touch, which only recognizes tap interactions, multi-touch can recognize more advanced interactions, like swipes, pinches, and rotations. These interactions are essential for current mobile devices.

The multi-touch technology existed already back in the '80s (Lee, Buxton&Smith 1985). However, it was not until Apple released the iPhone in 2007 that multi-touch interfaces got widespread in the consumer market. Touchscreen smartphones existed before the iPhone, but they were equipped with resistive touchscreens. Resistive touchscreens react to physical pressure, often require a stylus to handle, and are not multi-touch capable.

The benefit of multi-touch interfaces is the ability to tap directly on the touch keys. Multi-touch interfaces also allow users to directly manipulate objects by use of physical contact as if they were real-world objects. Pinch gesture can be used to zoom in and out of photos; swipe gesture to browse through photos; rotation gesture to rotate photos. The interaction of multi-touch interfaces is "natural" in the sense that it has similarities to the real world. Moreover, it can bring entirely new user interfaces dependent on the operation: digital keyboards for writing; number pads for the input of phone numbers; even digital instruments for music composition. Figure 4 shows the multi-touch interface of *GarageBand*, which is made for music composition, for iOS devices.

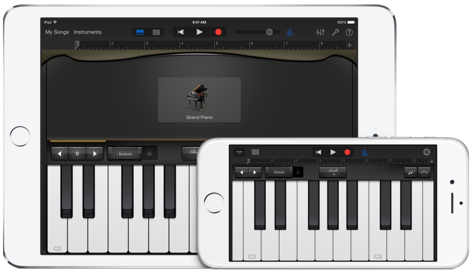

Figure 4: Press photo of GarageBand for iOS. Source: Apple

Today, capacitive multi-touch-screens are all over the marked: smartphones and tablets in various forms and sizes from different manufacturers, including Apple, Google, and Microsoft. Unlike resistive touchscreens, capacitive touchscreens react on electrical signals from the human body when physical contact occurs.

There is a big diversity in multi-touch devices and their utility. Microsoft has a 40" multi-touch based table, *Microsoft PixelSense,* made for industrial environments, like media, healthcare, and education. The electric car, *Tesla Model S*, has a 17" multi-touch display as an in-car system. HP has a computer model, *Sprout*, which does not come with traditional input devices like the mouse and keyboard. Instead, it has a projector that beams digital content directly to a multi-touch mat, working as a companion to the computer screen itself. HP has, in other words, replaced the traditional mouse and keyboard with multi-touch technology, as shown in Figure 5. These products indicate the high relevance and potential of multi-touch technology, how it forms current products, as well as future products.

Figure 5: Press photo of HP Sprout. Source: HP

2.1.3 Existing Mobile Solutions

The smartphone marked is currently dominated by two major mobile OSes—iOS and Android. iOS and Android were released in respectively 2007 and 2008, and are also available on portable media players and tablets while Android can run on computers as well.

iOS is developed by Apple and runs on iPhone, iPad, and iPod Touch. It was released in June 2007 and is currently on its eighth iteration. iOS is a closed source system and is based on

Darwin. Darwin is an open source OS developed by Apple, which also is the fundament to their computer system, OS X. The iOS kernel is, therefore, a closed source system based on open source components. Its current version is iOS 8; the latest smartphones running iOS are iPhone 6 and iPhone 6 Plus, with screen sizes on respectively 4.7" and 5.5".

Android is developed by Google and runs on smartphones, tablets, portable media players, and computers. It was released in September 2008. Android is an open source system, and its kernel is based on Linux. Linux is a free and open source OS created by Linus Torvalds and developed by thousands of contributors. Android comes in a wide variety of GUIs developed by different manufacturers. Android devices mostly come with third party proprietary components running on an open sourced kernel. Its current version is Android 5.0 Lollipop. The latest Android based prime models include Motorola Nexus 6, Sony Xperia Z3, and Samsung Galaxy S6, with screen sizes on respectively 6", 5.2", and 5.1".

2.1.4 Direct Manipulation

Most current GUIs are based on direct manipulation, which directly interacts with an object of interest. An example of direct manipulation in a mobile OS is to tap on an app icon to open the app.

Direct manipulation made computers more user-friendly compared to the complexed command-line interfaces (CLI). The term "direct manipulation" was first used in an academic paper in 1981 by Ben Shneiderman for the University of Maryland. Ben Shneiderman described the user experience of direct manipulation as follows (Shneiderman 1981, p. 57):

"Direct manipulation systems offer the satisfying experience of operating on visible objects. The computer becomes transparent, and users can concentrate on their tasks."

Moreover, some of the benefits of direct manipulation listed in the book *Interaction Design: Beyond Human—Computer Interaction* are as follows (Rogers, Sharp&Preece 2011, p. 51):

- helps beginners learn basic functionality rapidly
- experienced users can work rapidly on a wide range of tasks

- users experience less anxiety
- users gain confidence and mastery and feel in control

2.1.5 The GUI of iOS and Android

The GUI of iOS and Android share many similarities in terms of touch key locations. The touch keys are spread all over the screen, including the top corners. Both iOS and Android have most primary actions placed on the right side of the screen. Touch keys are only placed on the left side of the screen when the right side already is occupied. The placement of touch keys emphasizes that right-handed people are prioritized in the design process.

All screenshots examples from iOS and Android are respectively from an iPhone 6 (4.7" screen; iOS 8) and Google Nexus 5 (4.95" screen; Android 5.0 Lollipop).

iOS and Android have a very similar app screen as shown in Figure 6. Differences are that iOS' app icons are larger than Android's. The icons in iOS are also placed on the top of the screen while Android has a header that pushes the app icons away from the top edge. Android's solution makes it easier to reach when operating one-handed in the home screen.

Figure 6: Home screen in iOS (left) and Android (right).

Moreover, if we look at the alarm clock in iOS and Android, we can clearly see the emphasis for right-handed people. The activation buttons are all placed on the right side of the screen as shown in Figure 7.

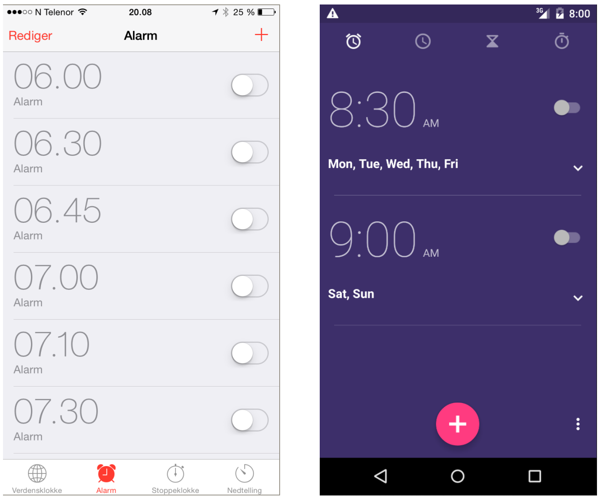

Figure 7: Alarm clock in iOS (left) and Android (right).

Figure 8 shows further examples of how interactive targets are placed on the right side of the screen. In the Photos app in iOS, the "Share" buttons are placed on the right side. In the browser tab view in Android, three interactive buttons are placed on the top right corner.

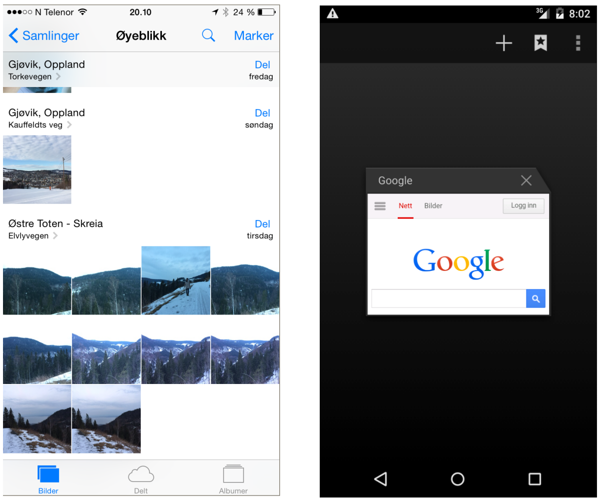

Figure 8: Photos app in iOS (left); browser tab view in Android (right).

iOS 8 has a function made specifically for one-handed interaction called *Reachability*. Reachability pushes the entire content on the screen downwards, closer to the thumb. It is activated by double touching[1] the home button. Apple's solution does not improve the actual GUI for one-handed optimization. It is rather a simple modification as an attempt to solve the reach problem.

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[1] Not confusing with double tap.

2.1.6 Repetitive Strain Injury

Repetitive strain injury (RSI) is a broad term used for a variety of disorders related to muscles, nerves, joints, and tendons. It often affects the forearms, hands, wrists, neck, back, and shoulders. Back pain is the most common RSI, but upper-limb related RSI has seen a rapid growth. It is one of the occupational disorders with fastest growth (Yassi 1997). RSI symptoms include pain, numbness, cramp, and stiffness. RSI is commonly linked to professions like office workers, carpenters, craft workers, and musicians. Activities that are prone to RSI include computer activities, music activities, and heavy manual work.

RSI is caused by repetitive tasks, bad postures, and other ergonomic risks, over an extended time. In relation to occupational RSI symptoms, common reasons include improper workstations and office environments, poorly designed equipment, static work, excessive working time, monotonous work, and lack of breaks. The risk to develop RSI is increased if several unergonomic factors are combined (Yassi 1997).

RSI has increased during the last decades and has reached epidemic proportions in certain industries. The large growth of RSI has been reported in numerous countries, including USA, UK, Norway, and Japan. Moreover, it costs the society large numbers to compensate for RSI related occupational illnesses. It is estimated a compensation cost over $20 billion per year in USA. In USA in 1990, more than 60% of occupational illnesses were related to RSI, and 1.9 million people suffered from carpal tunnel syndrome alone. The growth in occupational RSI symptoms are due to repetitive, rapid paced works, in addition to stressful environments caused by competitive businesses (Yassi 1997).

One of the most common types of RSI is *carpal tunnel syndrome*. Carpal tunnel syndrome is a hand and arm condition that occurs when the median nerve—a nerve that passes through the carpal tunnel in the wrist—is compressed. The symptoms of carpal tunnel syndrome are numbness and pain in the fingers, hand, and wrist. Weakness in the hand also normally occurs. Carpal tunnel syndrome is commonly known from the computer industry, by excessive typing on the keyboard, but it has lately also been reported to occur from smartphone usage (Shim 2012).

Tennis elbow (lateral epicondylitis) is another common type of RSI. It is a condition where the tendon outside of the elbow is strained. The symptoms of tennis elbow are pain on the outside of the elbow area. The term originated from the fact that many tennis players suffered from this injury, but it has lately become common in office jobs and from overuse of computer mice. A similar injury is *golfer's elbow* (medial epicondylitis), where the symptom occurs *inside* of the elbow in contrast to the tennis elbow.

De Quervain disease is an injury that can occur from smartphone usage. This injury is also commonly known as the *BlackBerry thumb*, named after the Canadian smartphone brand. De Quervain disease is a condition where the thumb's tendons are inflamed and compressed, which leads to pain in the thumb side of the wrist. The causes of de Quervain disease are normally associated with overuse of hand, wrist, and thumb.

2.1.7 Electromyography

Electromyography (EMG) is a technology used to measure muscle responses by recording the contractions of the muscles and nerves, and can be used to diagnose RSI. When the muscles are contracted, they produce electrical signals that the EMG instrument records. The process starts with electrical signals sent from the brain to the motor neurons through the nervous system. When the electrical signals are received by the motor neurons, the motor neurons then send electrical impulses to the muscles fibers. In health care, EMG is used to detect abnormal muscle activities in various diseases and physical conditions and is often combined with a nerve conduction study.

There are two commonly used types of EMG: *surface EMG* and *invasive EMG*. Surface EMG is technically limited compared to invasive EMG. As surface EMG records muscle contractions from the skin above the muscles—*voluntary motor activities*—the signals recorded are not as accurate as invasive EMG. Surface EMG is also noisier than invasive EMG. Invasive EMG has needle electrodes placed directly into the muscle fibers. Thus, it can record both *voluntary motor activities* and *insertional activities*. Invasive EMG shows activities that can clarify causes to an ongoing symptom, and it is the only type of EMG that can diagnose diseases consistently and accurately (Saponas et al. 2008).

2.2 Studies Related to One-handed Mobile Interaction

2.2.1 Analysis of One-handed Usability

When designing for one-handed mobile interaction, the type of thumb interactions and movements is crucial for the usability. Karlson et al. (2006) have done an empirical study about one-handed mobile interactions and thumb movements. They concluded that a north west to south east was the hardest movement to perform for right-handed users, regardless of the size of the device. The same study also reported that the size of the device itself is not as crucial as the touch key locations. This means that large smartphones could provide a higher usability for one-handed interaction if the GUI was presented differently. Park and Han's (2010b) study backs up the importance of touch key locations and touch key sizes in a touch interface. They have studied the impact of different touch key sizes (4 mm, 7 mm, and 10 mm), in addition to 25 different touch key locations. The results suggest that a touch key size of 10 mm provides the best usability. Touch key locations in the middle of the screen provide the best usability in terms of tapping convenience. Touch keys on the edge of the screen seemed to be awkward. The mean task completion time on the 4 mm touch keys (1455.3 ms) were slower to tap compared to 7 mm (1020.1 ms) and 10 mm (951.5 ms).

2.2.2 Virtual Thumb

As one-handed smartphone interaction can be challenging with the currents mobile OSes, there are many proposals of new functionalities to make it easier. Lai and Zhang (2014) have worked on a solution named *ExtendedThumb* shown in Figure 9, which is a virtual thumb to make one-handed interaction easier. The tool consists of a red visual cross that reaches targets the thumb otherwise does not reach. The user can change the direction and distance of the extended pointer with the thumb. *ExtendedThumb* gets activated when a double tap is performed on the screen.

Figure 9: ExtendedThumb. Source: Lai and Zhang (2014).

ExtendedThumb is reported to have helped the users hit targets with a high accuracy and has provided a high user satisfaction (5.81 of a 7-point Likert Scale question). Compared to direct touch (to touch with your physical thumb), ExtendedThumb is slower but has a lower error rate. Figure 10 shows the error rates of direct touch, ExtendedThumb, and another virtual thumb solution called *MagStick*. The evaluation were made with a laboratory experiment consisting of 33 participants where the task was to go through a target clicking game on a Samsung Galaxy Note II (5.5" display).

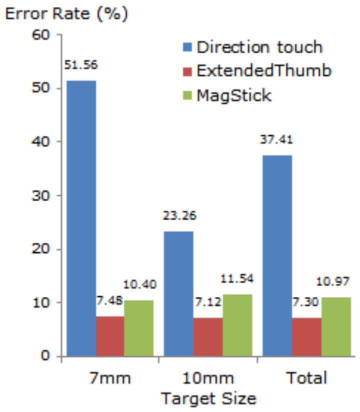


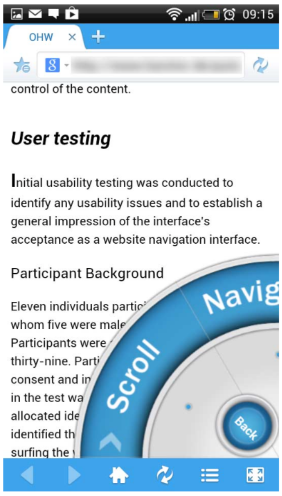
Figure 10: Error rates comparison, including the ExtendedThumb. Source: Lai and Zhang (2014)

However, *ExtendedThumb* is only an additional function to the mobile GUI. The activation approach may also be problematic if the user has to double tap the screen. The double tap interaction can interfere with the double-tap-to-zoom interaction many apps have, such as photo apps, maps, and web browsers.

ExtendedThumb can rather be considered as an alternative to Apple's *Reachability* functionality found on the iPhone 6 and the iPhone 6 Plus.

2.2.3 Modification of Websites for One-handed Mobile Interaction

In contrast to the ExtendedThumb, Seipp and Devlin (2013) have worked on a renewed user interface, designed for one-handed interaction. The interface is called *OHW* (One-Handed Website), shown in Figure 11, and is intended to be implemented on websites to make one-handed smartphone interaction easier. OHW is made with CSS3 and JavaScript technology.



control of the content.

User testing

Initial usability testing was conducted to identify any usability issues and to establish a general impression of the interface's acceptance as a website navigation interface.

Participant Background

Eleven individuals partic
whom five were male
Participants were
thirty-nine. Parti
consent and in
in the test wa
allocated ide
identified th
surfing the

Figure 11: OHW. Source: Seipp and Devlin (2013)

The interface of OHW is presented as a wheel that works as a navigation menu. It works similarly to the click wheel interface from the classic iPod models by Apple. The product is intended for web designers to implement on their websites. It looks for specific tags and codes on the website to present it with the OHW interface.

Seipp and Devlin (2013) conducted a study with 11 participants, where the users were asked to perform different tasks, including website navigation. The evaluated data and feedback show that OHW provides a good usability and efficiency.

OHW is also customizable for both right-handed and left-handed people—a function that neither iOS or Android allow today. The choice of customization for right-handed and left-handed users can provide better usability, as the differences in interaction between the preferred hand and non-preferred hand is large. Perry and Hourcade's (2008) study about one-handed thumb tapping on mobile touchscreen devices shows that by using your non-preferred hand on a smartphone, both accuracy and task duration see a negative impact. The accuracy goes down while task completion time increases. The effect was remarkable, and they suggest to evaluate touchscreen interaction with both the preferred and non-preferred hand.

2.2.4 The Functional Area

As the majority of the people prefer to interact with their smartphone one-handed (Karlson, Bederson&Contreras-Vidal 2006), some designers have been aware of the thumb's reach limitations. Luke Wroblewski (2011) has written a book about user experience for smartphones, called *Mobile First*. According to Luke Wroblewski, a user interface needs to pay attention to the functional area of the thumb[2] when designing for one-handed thumb interaction. If a user is holding a mobile device with the right hand, it is uncomfortable to stretch to the upper left corner, and vice versa for left-handed people. Bergstrom-Lehtovirta and Oulasvirta (2014) have scientifically investigated the functional area of the thumb in detail and has developed a model to predict the functional area. The intention of the model is to make it possible to reach any touch keys in the interface without changing the grip. The model calculates the functional area by the screen size of the device, hand size, and where the index finger is placed on the back of the device. The functional area is a relative area: the smaller the user's hand, and the larger the screen size, the smaller is the functional area. The basis of Bergstrom-Lehtovirta and Oulasvirta's (2014) model is similar to Luke Wroblewski's (2011) description of the functional area.

Luke Wroblewski (2011) suggests to place destructive actions outside of the functional area. Destructive actions can, for instance, be actions like cancel or delete. By placing these operations outside of the functional area, which is uncomfortable for the user to reach, it makes the user think thoroughly before hitting the touch key. Moreover, Luke Wroblewski suggests placing primary actions in the middle of the screen, making it easy and comfortable to reach, as shown in Figure 12.

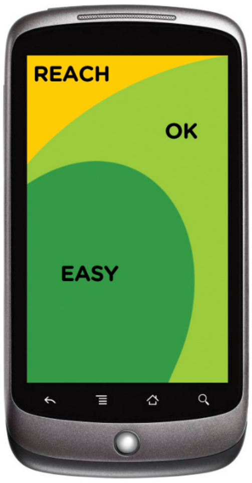


Figure 12: An example of the functional area. Source: Luke Wroblewski (2011, p. 73)

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[2] Luke Wroblewski (2011) refers to this area as "the comfort zone".

The functional area is individual from user to user and is affected by the physical dimensions of the mobile device (Bergstrom-Lehtovirta&Oulasvirta 2014). There is no single functional area that fits everyone. However, estimated functional areas following the principles from Luke Wroblewski (2011) and Bergstrom-Lehtovirta and Oulasvirta (2014) can be found for different devices. Figure 13 shows an estimated functional area—the green field—for the iPhone 6, which has a 4.7" screen, made by the designer Scott Hurff (2014) and published on his blog.

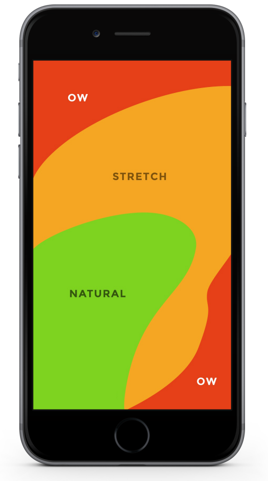


Figure 13: An estimated functional area for the iPhone 6. Source: Scott Hurff (2014)

2.2.5 New Input Approaches

Some researchers have proposed new interaction approaches that are not directly related to the GUI. *Unifone* by Holman et al. (2013) is an example, which takes use of the supporting fingers—the auxiliary fingers—as an input approach. Unifone takes advantage of the auxiliary fingers that would otherwise be used to grip the device. Holman et al. have investigated how squeeze-based gestures could be used for common touch interactions. Figure 14 illustrates the concept of Unifone.

Figure 14: Unifone. Source: Holman et al. (2013)

Unifone was made by attaching a metal sensor to the right side of an iPhone 4s. The metal attachment had sensors on the top, middle and bottom area that register when the user is squeezing his/her fingers on three different locations. The prototype was tested on 10 participants. The tasks consisted of scrolling, map navigation, text formatting and application switching.

Holman et al. (2013) reported that Unifone can improve the performance of one-handed interaction when used to control isometric gestures. The results showed that direct scrolling was 28% slower than the ordinary thumb-only input; the formatting task 25% faster; the application switching 9.8% faster, and the map navigation 12.5 % faster. As they stated, the results could be different if the sensor attachment was part of the phone's actual design.

However, the study could have been improved in respect to large smartphones. The prototype was tested on an iPhone 4s, which has a 3.5" display. The display size of the iPhone 4s is identical to the first generation iPhone launched in 2007, which is one of the earliest multi-touch smartphones that entered the marked. A 3.5" screen is therefore not considered as large. Furthermore, in the time the study was conducted the iPhone 4s was one of the *smallest* smartphones available. It would be of relevance to see a new study of Unifone conducted on a larger smartphone, like the iPhone 6, iPhone 6 Plus, or some Android phones.

Boring et al. (2012) have developed a prototype called *The Fat Thumb.* The concept of The Fat Thumb is to replace the pinch to zoom gesture. The Fat Thumb changes from panning to zooming fluidly in one gesture. The prototype takes advantage of the thumb's contact size for the system to recognize if the user wants to pan or to zoom. The thumb's contact size is the size of the thumb that is in physical contact with the screen. With a small contact size, the user does a pan as he normally does; with an increased contact size the user does a zoom by moving the thumb upwards or backward. The solution of The Fat Thumb corresponds to the findings from Park and Han's (2010a) study, where they reported that different touching methods had different contact size. Park and Han found that a *vertical touch* has a smaller contact size and is more accurate than an *oblique touch*. The Fat Thumb by Boring et al. (2012) uses the vertical touch to pan and the oblique touch to zoom. Figure 15 shows the two different touching methods as reported in the study by Park and Han (2010a).

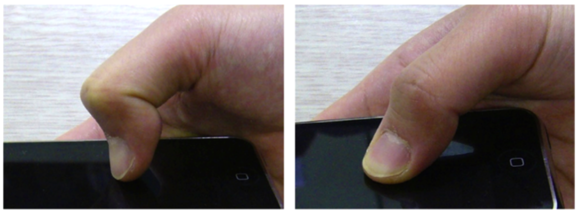


Figure 15: Vertical touch (left) and oblique touch (right). Source: Park and Han (2010a)

Boring et al. (2012) also tested the prototype against other input alternatives developed by other researchers, namely *Slider*, *CycloStar*, and *Tilt-to-Zoom*. The results were clear: FatThumb outperforms the other alternatives in task time, error rates, and least amount of strokes, in addition to being the most subjective preferred technique by the participants. Figure 16 shows the results.

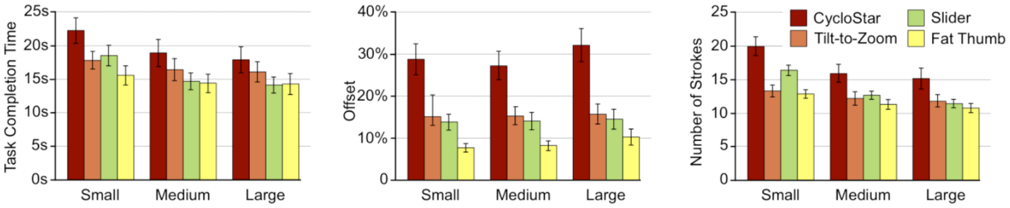


Figure 16: FatThumb compared to other input alternatives. Source: Boring et al. (2012)

The study was done with an iPhone 4, which has a 3.5" screen. Similar to Holman et al. (2013), the team behind *The Fat Thumb* could have done a more convincing study if they had used a bigger phone. Boring et al. (2012) also stated that they will do a further study on a bigger variety of tasks as well, as this study only tested pan and zoom in the iOS' integrated *Maps* app.

2.3 Studies Related to Mobile Devices and Health Risks

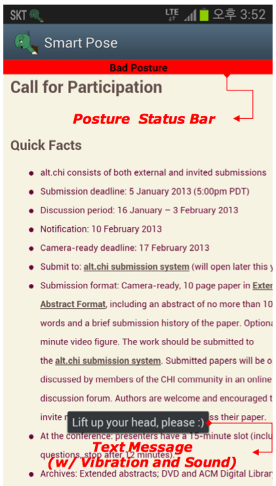
2.3.1 Detecting Bad Postures in Smartphone Usage

Proposals for new mobile solutions have not only been in terms of interactions, but also related to health. RSI is one of the fastest growing occupational illnesses and has even reached epidemic proportions in certain industries (Yassi 1997). Health and ergonomics are crucial factors in an era dominated by technology. Thus, there are many studies related to the ergonomics of mobile devices. Use of mobile devices are straining our muscles (Bachynskyi et al. 2015), and overuse of smartphones can lead to RSI, such as carpal tunnel syndrome

(Shim 2012). RSI typically occurs from repetitive motions, and awkward and unnatural postures (Yassi 1997).

The widespread of smartphones has exposed many people to awkward postures over an extended time. Researchers have developed different solutions to prevent unhealthy postures, which can cause different musculoskeletal issues. Lee et al. (2013) have made a mobile posture-aware system, called *Smart Pose*, which monitors if the user's neck is bent to prevent a chronic strain in neck and back muscles. It uses the smartphone's internal components to detect a bad posture. The components were the front faced camera, 3-axis accelerometer, and orientation sensor. The user gets notified if a bad posture is detected.

An application was developed for Samsung Galaxy S3, which has all the required internal sensors. Official Android application programming interfaces (APIs) were used to face detection and shake and tilt angle calculation. Figure 17 shows a warning message when the system detects a bad posture.



Call for Participation

Quick Facts

- alt.chi consists of both external and invited submissions
- Submission deadline: 5 January 2013 (5:00pm PDT)
- Discussion period: 16 January – 3 February 2013
- Notification: 10 February 2013
- Camera-ready deadline: 17 February 2013
- Submit to: alt.chi submission system (will open later this
- Submission format: Camera-ready, 10 page paper in Exter Abstract Format, including an abstract of no more than 10 words and a brief submission history of the paper. Option minute video figure. The work should be submitted to the alt.chi submission system. Submitted papers will be o discussed by members of the CHI community in an online discussion forum. Authors are welcome and encouraged t invite r ss their paper.
- At the conference: presenters have a 15-minute slot (inclu questions, stop after 12 minutes).
- Archives: Extended abstracts; DVD and ACM Digital Librar

Lift up your head, please :)

Figure 17: Warning message from Smart Pose. Source: Lee et al. (2013)

Similar to Smart Pose, Baek and Yun (2010) have developed a user posture monitoring system. It is based on a tilt-angle measurement algorithm that uses a two-axis accelerometer and can detect bad postures when sitting, standing, and walking. The system was implemented on a PDA and tested on ten participants. Its intention was to detect bad posture when the participant was watching a movie. The results showed that the recognition rate was greater than 99%.

El-Sayed et al. (2011) have also developed a system to detect bad postures. It has integrated posture sensors and strain sensors to detect spine stress at both the back and the feet. The system notifies the user by use of SMS when bad posture is detected, in addition to emails with a summary of the daily activities. The summary emails contain information like the amount of time spent sitting, standing, or walking, and the daily average posture angle. Unlike the aforementioned posture monitoring systems, El-Sayed et al.'s solution requires wearable components to work. This makes it unpractical for everyday use compared to a solution that only uses the smartphone's internal components.

2.3.2 Health Risks Related to Different Mobile Devices

As smartphones are not the only type of devices that can cause musculoskeletal issues, there are studies that investigate the adverse physiological responses from other types of mobile devices as well. Bachynskyi et al. (2015) did a biomechanical simulated study of different touchscreen devices. The biomechanical simulation uses muscle activation, forces and moments at joints, velocities and angles of limbs to describe motion capture data. The researchers claim that it was the first work at comparing the different touch surfaces in terms of performance and ergonomics. They compared the following devices: public display, tabletop, laptop, tablet, and smartphone. Biomechanics simulation and optical motion capture suit were applied to the study as measuring instruments. The performance of the public display had to be done standing while the remaining devices were performed sitting. For the sitting tasks, they built a chair with sensors to record external forces. Performance on each device consisted of 12 conditions; each condition consisting of 50 repetitive aimed movements. 40 participants were recruited to the study.

Bachynskyi et al. (2015) reported clear differences in performance and muscle strain to the different devices. The interactions of the different devices appear nevertheless very similar. The investigation of smartphone usage contained both one-handed and two-handed interactions. Two-handed interaction had higher performance than one-handed interaction. Both of the approaches were bad for long-term use, meaning that smartphone usage, in general, is unergonomic. When analyzing the posture in the different performances, they found more clusters in one-handed (4 clusters) than two-handed interaction (3 clusters). Use of tablets was obtained to have the most amount of clusters (7 clusters). They discovered that the back, shoulders, and elbow of the holding arm were the muscles activated when interacting with a smartphone. The representative smartphone device was a Samsung Galaxy S3, equipped with a 4.8" screen. Figure 18 shows the total muscle activation on the different surfaces, showed in confidence intervals.

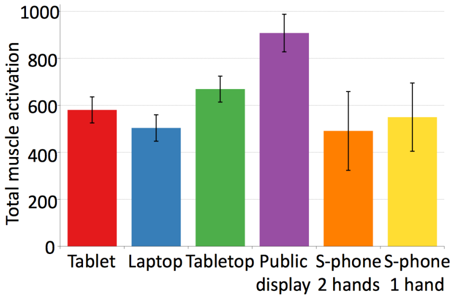


Figure 18: The results in total muscle activation. Source: Bachynskyi et al. (2015)

Stawarz and Benedyk (2013) have done a detailed study of primarily tablet usage and its risks to RSI. The study investigated specifically office workers who use tablets as office work tools, and consisted of a questionnaire, interviews, and observations.

44% of the respondents had health issues: visual impairments (18%), back problems (17%), and RSI (9%). The majority (59%) of the respondents used their tablets 1–2 hours for work purposes on a daily basis. It was also reported that the tablets were frequently used for work purposes during the commute or while traveling. Some common tasks were reading and responding to emails, surfing the web, and reading documents. Pains and discomfort were reported to occur in the neck, shoulders, eyes, and wrists. 66% of the respondents occasionally suffered from discomfort from tablet usage.

The results from the interviews show that several devices were used in different contexts. These devices were tablets, smartphones, and laptops. Use of tablets was mostly done during commuting, or as replacement of a laptop, for instance at meetings. The observations show that all participants had bad posture when using a tablet, which shows that bad posture is not exposed from smartphone usage alone. The bad posture made the neck, back, elbow, shoulders, and wrists prone to injuries. Stawarz and Benedyk (2013) report, however, that it is hard to determine one single device as a source for injuries when several portable devices often are interchangeably used by tablet users. Some users also already suffered from RSI. Thus a single source for musculoskeletal issues was hard to point out.

2.3.3 EMG Studies of Smartphone Interaction

Choi et al. (2013) have analyzed the discomfort of different touch key locations on a digital keyboard on smartphones. EMG was applied to the study. The different touch locations consisted of a 5 x 5 grid on the screen. They measured four different muscles, namely *abductor pollicis longus (APL)* and *extensor digitorum communis (EDC)*, which are on the forearm, and *abductor pollicis brevis (APB)* and *first dorsal interossei (FDI)*, which are part of the thumb. In addition to EMG, which is an objective index, they also applied the Borg Scale for subjective measuring purposes. Unlike many studies about touch interactions on smartphones, this study investigated the ergonomics of typing on a touchscreen with two hands.

The level of perceived discomfort, following the Borg CR10 Scale (which is one specific type of the Borg Scale), was reported to be significantly different from the touch points, and that the maximum value of discomfort was 3.5 times more than the minimum (2.5 vs. 0.7). However, the perceived discomforts were not significant between the right and left thumb. The results showed that the perceived discomfort was highest in the middle column, and in the first and last column (closest to the left and right edge of the screen). Perceived discomfort was also high in the two bottom row of the screen. They discovered a tendency that the locations furthest away from the initial location of the thumb provided the highest perceived discomfort. Furthermore, the results from the EMG data were only significant across touch rows and columns. The EMG data also showed that the left thumb's APB in ascending order increased on first, second, and third columns. The data for the right thumb's APB similarly increased in ascending order on fifth, fourth, and third columns.

Xiong and Muraki (2013) have investigated smartphone operation and muscle fatigue with the use of EMG instruments. The study investigated tapping, moving, and circling as the specific thumb movements, performed on an experimental smartphone mockup. *Abductor pollicis brevis (APB)* and *first dorsal interosseous (FDI)* were the two muscles measured. The conclusion of the study was that touch key size and thumb moving orientation affect the thumb performance. Small buttons and flexion-extension orientation increase muscle fatigue in *first dorsal interosseous,* which is a prime muscle for thumb movements.

2.4 Pre-study

A pre-study was conducted in the fall semester 2014, as part of the course *IMT4882 Specialization Course 2.* It was an empirical study about one-handed interaction of large smartphones. It compared how users perceive and perform an identical mobile platform on a large smartphone and a smaller one (Nguyen 2014). The pre-study was a descriptive research, which is a type of research that determines that something certain is happening (Lazar, Feng&Hochheiser 2010). The results show that people find one-handed interaction of large smartphones uncomfortable, and made the basis for the research questions in this master thesis.

2.4.1 Experimental Design

The participants performed a set of five tasks both on an iPhone 5 and an iPhone 6. All the tasks were basic smartphone functions and consisted of swipe and tap interactions. Every participant went through all the different conditions, which makes it a within-group design. Task completion time was measured, and the participants would by the end of the investigation determine whether the iPhone 5 or iPhone 6 was the preferred device for one-handed interaction.

The performance of the tasks had to be one-handed; support of a second hand was not allowed. The dominant hand that operated the smartphone had to be kept in the air. The participants performed the tasks while sitting, in a furnished laboratory at Gjøvik University College. The tasks were as follows (Nguyen 2014, p. 7):

1. *Open the Message app; compose a new message; write "Hi, it's me!" and send it to Phuong Nguyen.*
2. *Open Maps and search for "Oslo Central Station".*
3. *Open the Phone app and call 473 51 055.*
4. *Open the Camera app and switch through three different camera functions.*
5. *Open Safari web browser and navigate to www.apple.com.*

The tasks were followed by three main questions, which determined the participant's subjective preferences (Nguyen 2014, p. 8):

1. *Which phone did you prefer to use one-handed?*
2. *Do you prefer to use your phone one-handed or two-handed?*
3. *How often is one of your hands occupied by a shopping bag, umbrella, etc.?*

In addition to the questions, the research also measured the task completion time performed by the participants. The purpose was to have an objective index to compare to the subjective data. However, it mainly focused on the participant's preferences, as the research emphasized the perceived user experience.

2.4.2 Research Instruments

An iPhone 5 (4” screen) and an iPhone 6 (4.7” screen) were used to have the same mobile platform on both devices. Both devices’ home screen and organization were set up identically to avoid biases in the experimental procedure. Each participant’s performance was video recorded to measure the task completion times. The recording was done with a pair of eye tracking glasses, namely SensoMotoric Instruments (SMI). Gaze data was collected with the software SMI BeGaze 3.5. The recorded material consisted of both picture and sound, and was exclusively used for measuring purposes. Two notebook computers were used: one to save the video recordings; the other to note down the participants’ answers to the follow-up questions.

2.4.3 Experimental Procedure

The investigation started with a verbal explanation of the research, followed by a handout of a written inform consent. When the participant confirmed their voluntary participation, and the fully understanding of the terms as a volunteer, their dominant hand was outlined on a blank sheet. The outline was later used to measure every participant's thumb and hand length. The thumb length was measured from the bottom of the palm to the top of the thumb; the hand length was measured from the bottom of the palm to the top of the middle finger. The outlines were later measured with a ruler in millimeters (mm).

Six participants owned an iPhone, so they started directly on the study tasks. Those not familiar with an iPhone and iOS had got guidance through the tasks before the video recording began. The investigation had no intention to address the learnability of iOS, but rather attempted to make every participant familiar with the system before the tasks began. The video recording did not start until the participant was fully familiar with how to perform all the five tasks. All of the apps that were used in the study were collected on one single home screen, making it easy for the participant to find the different functionalities. The apps that were not part of the study were hidden to avoid disturbances.

2.4.4 Results

14 participants (seven male; seven female; age 22–26) were recruited to the study. One was left-handed. None suffered from RSI. The participants' thumb length was between 142mm–165mm (mean length at 152mm), and hand length between 175mm–211mm (mean length at 191mm). All participants were familiar with and owned a touchscreen smartphone. Six participants used an iPhone model prior to iPhone 6 on a daily basis. The iPhone models prior to iPhone 6 have 3.5" and 4" displays.

13 out of 14 participants (93%) preferred the small device for one-handed interaction; one participant (7%) preferred both devices equally. The majority of the participants found the large device inconvenient to use because they had to change grip position.

Furthermore, 10 out of 14 participants (71%) preferred to operate a smartphone one-handed. Four (29%) preferred to use a smartphone with both hands. Half of the participants reported that their second hand often is occupied by other things, including bags, umbrellas, etc. Two participants (14%) reported that it happens now and then. Five participants (36%) reported that it happens rarely.

A paired samples t-test was performed on the task completion times. The results show that only task 1 was statistically significant ($t = -2.229$, $P < 0.05$) faster on the small device than on the large device. All the remaining tasks were however performed faster on the large device by a small margin (between 0.22–1.03 seconds faster). The results suggest that user satisfaction not always necessarily correlate to objective usability metrics, as also noted by the famous HCI researcher Jakob Nielsen (2012).

This study had a major weakness, and it was the lack of randomization. Neither the order of the tasks or the order of the small/large device were randomized. The task completion times could be affected by the learning effect, given that the order was the same on both the small and large device. Since the tasks always started on the small device, there were chances that the participants became familiar with the tasks when performing on the large device. This could possibly be the reason that the subjective preferences and task completion times did not correspond.

3 Methodology

In order to examine the research questions, listed in chapter 1.2, two types of research were conducted: expert interviews and an EMG test. The main purpose of the expert interviews was to get a basis to form the hypotheses for the EMG test. The EMG test was the main research of this master thesis.

The EMG test examined different touch key locations and touch key sizes and the functional area in a mobile user interface. It focused on one-handed smartphone interaction and recorded the physiological responses to the different user interfaces. It generally examined different touch key locations and touch key sizes in a user interface, rather than specific mobile OSes. Moreover, the EMG test compared the participant's subjective perceived exertion, using the Borg Scale, to the results from an objective index, the EMG output.

This chapter consists of two parts: one for each research. Section 3.1 addresses the expert interviews. Section 3.2 describes the EMG test.

3.1 Expert Interviews

The expert interviews addressed the relation between smartphone usage and RSI. It examined how the current mobile systems are in terms of ergonomics, how RSI occurs from smartphone usage, and if the principles of the functional area could have a positive effect to the ergonomics. This research was relational, which documents that one specific factor correlates with another factor (Lazar, Feng&Hochheiser 2010). In this case, the expert interviews determined that there are correlations between RSI and heavy use of smartphones, and that the user interface can affect the level of muscle contraction. The expert interviews were conducted during January and February 2015 and collected qualitative data from eight physiotherapists.

3.1.1 Interview Design

The interviews conducted were semi-structured, meaning that follow-up questions could be asked if appropriated. It also let the interviewees discuss outside of the interview questions. This type of interview is appropriated to go deeper into a specific topic (Lazar, Feng&Hochheiser 2010). Six of the interviews were written; two were verbally conducted in person. The choice of interview method depended on the physiotherapist's time schedule and preference.

The interview consisted of nine questions related to RSI, smartphones, the human physiology, and digital systems in terms of ergonomics. The oral interviews were conducted at the interviewee's office and at school. The written interviews were sent as a document on email and Facebook. The answers from the interviewees were submitted with the respective medium.

3.1.2 Interview Procedure

There were no time limits for the interviewees when conducted verbally. The written interviews had no specific hand-in deadline, but the interviewees were urged to respond within a week. All the interview questions were open questions. Additional questions could be asked, which is a characteristic of a semi-structured interview.

The verbal interviews were audio recorded with an iPhone that later were transcribed into text. Spoken conversations are hard to note down due to the fast pace, thus a recording made it easier to focus on the conversation. Moreover, recorded materials keep the exact information provided by the interviewees, including all details that could have been gone if written down.

Content analysis was applied to the interview data. Content analysis is a commonly used qualitative data analysis technique that involves inspection of different patterns, including frequency of terms and co-occurrences (Lazar, Feng&Hochheiser 2010).

3.2 EMG Test

The EMG test addressed the physiological responses related to various user interfaces when operating a large smartphone one-handed. In addition to EMG, which is an objective measuring index, Borg Scale was also applied as an index for subjective perceived exertion. The Borg Scale is a method used to quantify subjective discomfort and can be applied to nearly all people. The EMG test was an experimental research, which attempted to establish causation between two different factors (Lazar, Feng&Hochheiser 2010). It was conducted in mid-April 2015 and collected quantitative data from both objective and subjective indexes, from respectively EMG and Borg Scale.

3.2.1 Hypotheses

The experiment had three hypotheses made of the most remarkable inputs from the expert interviews. All the hypotheses were related to user interface design by examining different touch key positions and touch key sizes. They all applied specifically to smartphone GUIs:

1. Touch keys inside the functional area expose less muscle contraction than touch keys outside the functional area.
2. A GUI designed for the user's preferred hand exposes less muscle contraction than a GUI not designed for the user's preferred hand.
3. Large touch key sizes expose less muscle contraction than small touch key sizes.

3.2.2 Tasks

The tasks applied in the test were inspired by the multi-directional tapping task proposed by the ISO 9241 standard. International Organization for Standardization (ISO) is an independent organization that develops worldwide standards to ensure quality, safety, and efficiency. ISO gives specifications for products, services, and systems in a wide range of industries. The ISO 9241 standards cover the ergonomics of human—computer interaction. The ISO 9241-400 is a set of "principles and requirements for physical input devices," including touchscreens (ISO 2007).

A common multi-directional tapping task looks like the Figure 19. The highlighted target—the blue dot—changes position when the participant taps it. However, this study's multi-directional tapping task did not follow the circular layout, as it was not applicable to investigate the functional area proposed by Scott Hurff (2014). It had instead a matrix of touch keys spread over the whole screen, as shown in Figure 20. The tasks were composed of multiple photos linked together and exported to a clickable PDF. The photos were made in Adobe Illustrator CC 2014, and was linked together and exported to PDF in Adobe Fireworks CS6.

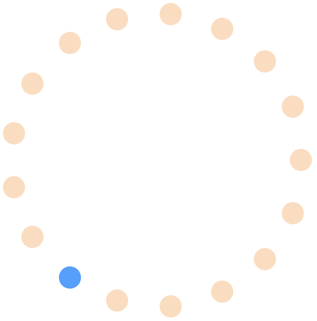


Figure 19: A common multi-directional tapping task.

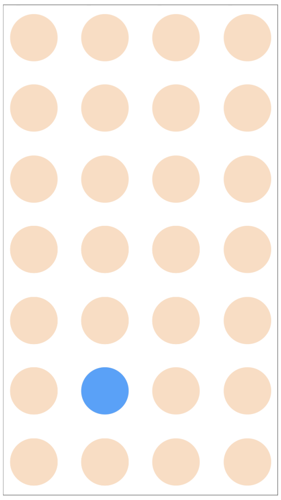


Figure 20: The multi-directional tapping task applied to the test.

Figure 21 illustrates the estimated functional area on an iPhone 6, beneath the touch keys. Only the green (comfortable) and red (uncomfortable) areas were used for the tasks. There were six tasks in total. Each task consisted of 20 aimed targets, which in total were 120 aimed targets (20 x 6).

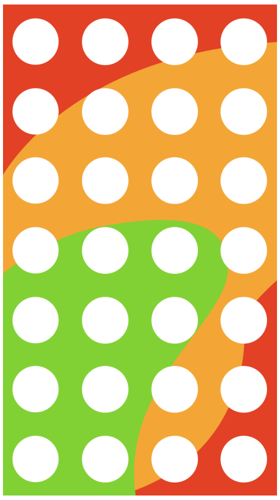


Figure 21: The functional area proposed by Scott Hurff (2014).

The prototype used complimentary colors for visibility purposes. Complimentary colors are pairs of colors that create the strongest contrasts. The neutral touch keys were orange; the highlighted touch key was blue. The highlighted touch key changed position for every tap performed by the participant. Default touch key size was 10 mm in diameter. The location of the highlighted touch keys depended on the task's purpose, which were kept secretly for the participants. This was to avoid biases on the determination of subjective perceived exertion, following the Borg Scale. Figure 22 shows the task prototype.

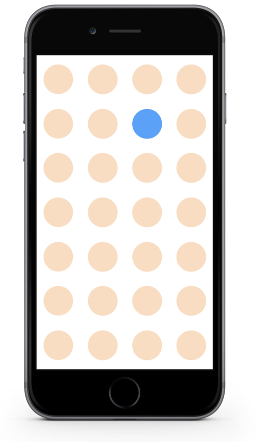


Figure 22: The applied multi-directional tapping task.

The tasks were as follows:

1. **Small touch key size:** *7 mm; targets spread over the whole screen*
2. **Medium touch key size:** *10 mm; targets spread over the whole screen*
3. **Large touch key size:** *13 mm; targets spread over the whole screen*
4. **Ergonomic touch key locations intended for left-handed users:** *10 mm; green area*
5. **Ergonomic touch key locations intended for right-handed users:** *10 mm; green area*
6. **Unergonomic touch key locations:** *10 mm; red area*

Task 1, 2, and 3

Task 1, 2, and 3 examined the different touch key sizes and had targets spread over the whole screen independent of the functional area. The targets and order were identical on these three tasks, as their intention was to have only one difference: the touch keys size. These three tasks were later compared to each other to investigate the third hypothesis: *Large touch key sizes expose less muscle contraction than small touch key sizes*. Figure 23 shows the three different touch key sizes, respectively 7 mm, 10 mm, and 13 mm.

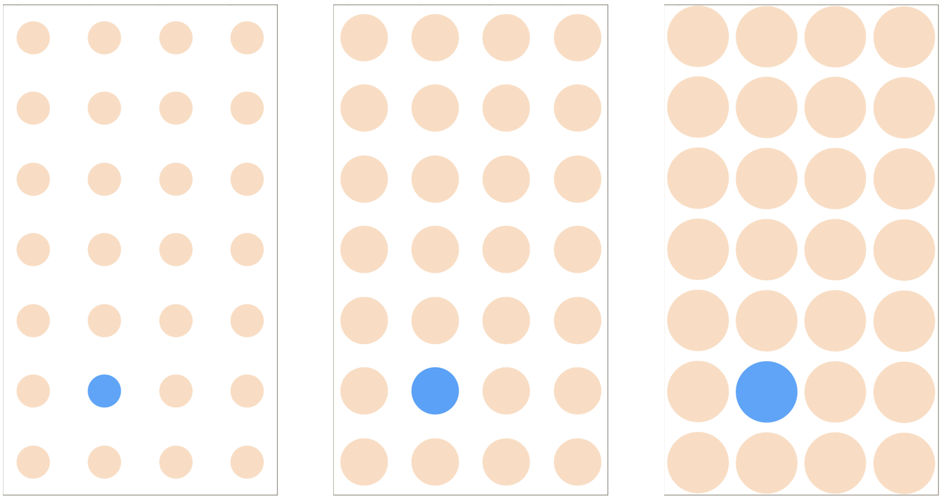


Figure 23: 7 mm (left), 10 mm (middle), and 13 mm (right) touch key sizes.

Task 4 and 5

Task 4 and 5 examined the functional area. These two tasks investigated both the first and the second hypotheses: *1) Touch keys inside the functional area expose less muscle contraction than touch keys outside the functional area*; and *2) A GUI designed for the user's preferred hand exposes less muscle contraction than a GUI not designed for the user's preferred hand.* Task 4 or 5—depended on the participant's dominant hand—were later compared to task 6 to investigate the first hypothesis. Moreover, task 4 and 5 were compared to each other to investigate the second hypothesis. They were a visually mirrored version of one another and both had 10 mm touch key size, as shown in Figure 24.

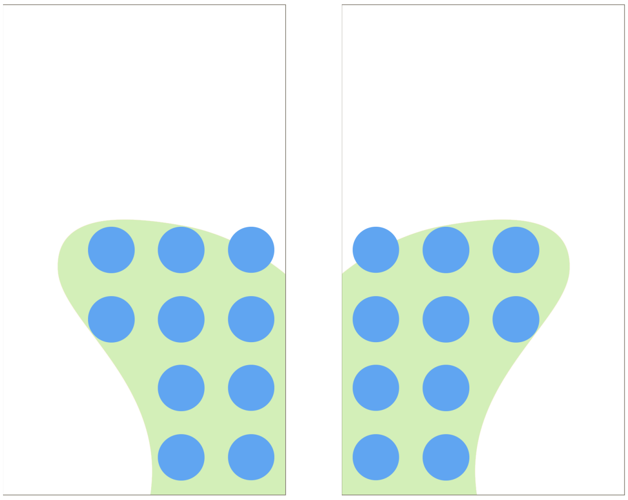


Figure 24: Estimated functional area for left-handed (left) and right-handed (right).

Task 6

Task 6 examined the locations outside of the functional area. The task consisted of the touch keys shown in Figure 25, which were 10 mm in touch key size. This task was compared to task 4 and 5 to investigate the first hypothesis: *Touch keys inside the functional area expose less muscle contraction than touch keys outside the functional area.*

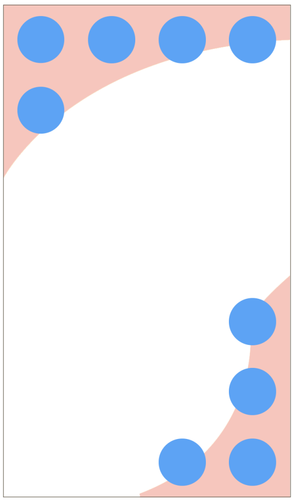


Figure 25: Task 6 was designed to be uncomfortable.

3.2.3 Experimental Design

The design of the experiment was a *within-group design*, which means that every participant went through all the different conditions. Moreover, it was a *true experiment*. A true experiment contains multiple conditions and random assignment.

Within-group design was chosen because physiological responses are highly individual (Bloom et al. 1976; Hautala et al. 2006), which would make the data more valid if every participant performed all the conditions. The biggest challenge of a within-group design is the potential *learning effect*—a term used when the participant learns from the experience and become better during the performance. *Fatigue* is considered as another potential challenge of a within-group design (Lazar, Feng&Hochheiser 2010). As the experiment applied randomization to the tasks to every participant, both the *learning effect* and *fatigue* were effectively controlled. Moreover, the *lack of* randomization was an experimental weakness in the pre-study. Thus, it was important to apply randomization to this research as it was vital that the EMG data was not biased.

This research is defined as a true experiment because it fulfills the following characteristics (Lazar, Feng&Hochheiser 2010, p. 42):

- Based on several research hypotheses
- Contained multiple conditions
- The depended variables are of the quantitative type
- Various statistical significance tests were performed to analyze the results
- Designed to remove potential biases
- Fully replicable by other experimenters, with different participants, at different times, and in different locations

3.2.4 Research Instruments and Set-up

In order to conduct the experiment, the investigation applied following tools, instruments, and experiment set-up. All the EMG tools utilized in this research belong to Lillehammer University College (LUC), and was formally loaned to Gjøvik University College. The loan of the EMG tools was done by LUC's terms and conditions.

iPhone 6

The different tasks were presented on an iPhone 6 (4.7" screen; 138.1 mm height; 67.0 mm width; 6.9 mm depth; 129 grams weight), which is Apple's last generation smartphone. The iPhone 6 is the second largest iPhone, after the iPhone 6 Plus (5.5" screen; 158.1 mm height; 77.8 mm width; 7.1 mm depth; 172 grams weight). However, the iPhone 6 is Apple’s most popular smartphone as of today (Campbell 2015). It is, therefore, a good representation for “large smartphones”.

Biopac MP36

A surface EMG machine was applied to measure muscle contractions, namely the model *Biopac MP36*. Surface EMG was chosen because invasive EMG was unappropriated with its intramuscular electrodes that provide physical discomfort. Furthermore, people without a medical background can conduct surface EMG with minimal risk to the test subject (Day 2002).

Biopac SS2L Electrode Lead Set

The applied electrode cable was of the type *SS2L* and was equipped with three pinch leads to snap on disposable electrodes. The electrode cable was connected to the Biopac MP36 hardware.

Biopac EL503

Biopac EL503 is disposable, gelled vinyl electrodes that were applied to the test, shown in Figure 26. Gelled electrodes were the chosen type of sensor because of the good attachment properties if applied properly. This makes it possible to test rapid movements without displacements of the electrodes (Day 2002). The diameter of the electrodes was 35 mm.

Figure 26: Biopac EL503 electrodes that were applied to the experiment.

Biopac Gel 1010

An isotonic recording gel, *Gel 101* by Biopac, was applied on the electrodes to strengthen the signals of the recording.

Biopac Student Lab 4.0 MP36

Biopac Student Lab 4.0 MP36 is the accompanying software to the EMG hardware. Biopac Student Lab 4.0 MP36 was, in combination with the Biopac MP36 hardware, used to record the EMG data. Biopac Student Lab 4.0 MP36, as shown in Figure 27, was the software used to analyze the collected EMG data.

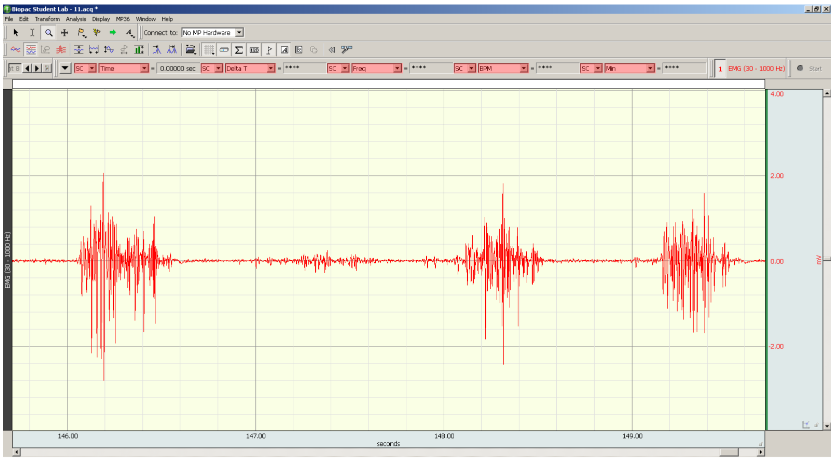


Figure 27: Biopac Student Lab 4.0 MP36.

Two Computers

Two computers were used in the investigation. One to record the EMG signal with the accompanying software. The other computer was used to note down participant info and to run a timer app to control the duration of the breaks.

Set-up

The investigation was conducted in a furnished laboratory at GUC. Two tables were applied to the set-up. As EMG is sensitive to electricity, the computers were placed on different tables as an attempt to control the ambient noise. Figure 28 shows one of the two tables used in the investigation.

When measuring EMG signals, there are two types of noise to be aware of: *ambient noise* and *transducer noise*. Ambient noise occurs from electrical devices, such as computers, power lines, and fluorescent lights. Transducer noise occurs at the electrode to skin junction (Day 2002).

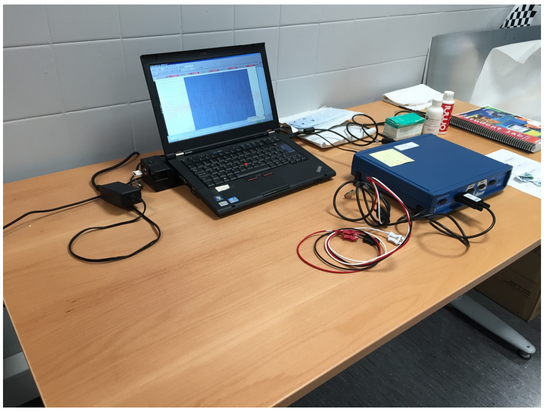


Figure 28: Each of the two computers had its own table.

3.2.5 Experimental Procedure

Pilot Study

A pilot study was conducted two days before the experiment to ensure that everything worked as planned. A pilot study can identify potential biases, such as inappropriate measurement instruments, and flaws in the experimental procedure. It was conducted on a test person from the target group. The conduction showed that the experimental procedures worked well. The generated data also seemed to be clear and of high quality.

Introduction

The experiment started with a verbal introduction about the master thesis, the background, the purpose of the EMG test, and practical information about being a participant. The informed consent was after that handed out. When the participant confirmed an agreement, personal information about the participant's gender and dominant hand was written down in an Excel document. Furthermore, the hand and thumb length of the participant's dominant hand was measured, in the same procedure applied to pre-study conducted in *IMT4882 Specialization Course II* (Nguyen 2014). The participant was told to place their hand on a sheet of paper, making an "L" shape with their dominant hand while it was outlined with a pen. The outlines were later measured with a ruler. The procedure worked well in the earlier aforementioned pre-study conducted last semester (Nguyen 2014). Thus, it was applied to this experimental design as well.

Attachment of Electrodes

The electrodes were attached to the participant's dominant hand. Since EMG instruments record the electric activities in muscle contractions, the placement of the electrodes is vital for good signals. There were three electrodes in total, which were placed on the participant’s *abductor pollicis brevis (APB)*, *abductor pollicis longus (APL)*, and *first dorsal interossei (FDI)* on the participant's dominant hand. All these muscles were also measured in the related study by Choi, Park, and Jung (2013), while APB and FDI were specifically the two muscles measured in the study by Xiong and Muraki (2013). The choice of placement of the electrodes was because these muscles take part in the gripping (Gustafsson, Johnson&Hagberg 2010). Moreover, the APB and APL are directly related to the movement of the thumb (Choi, Park&Jung 2013). The recording of the EMG was set to a 30–1000 Hz sampling rate. Figure 29 shows the placements of the electrodes.

Figure 29: The placement of the electrodes.

To keep the wires of the EMG detectors uncluttered, a sports tape was used to attach the wires to the participant's dominant hand as shown in Figure 30. This would also lead to more accurate muscle recording, as the wires were better controlled. The electrodes were attached to the exact same skin location on all participants. An isotonic recording gel was applied on the center of the electrodes to get better signals, as shown in Figure 31. The contact quality between the electrodes and the skin was controlled to be consistent. Moreover, the same type of electrodes and amplifier were used throughout the whole test. These procedures reduced the variability of the EMG signal, making it easier to interpret the data (Day 2002). Only muscle contractions were measured; nerve conductions were not part of the study.

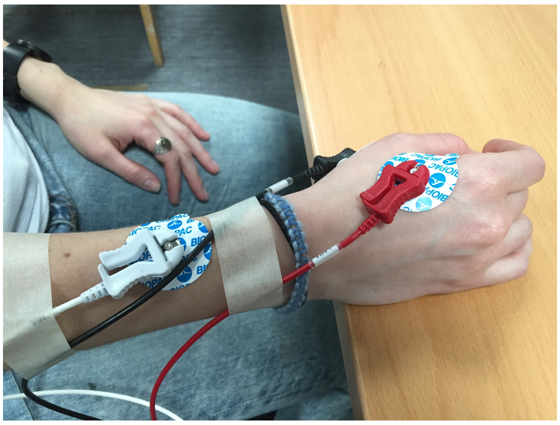


Figure 30: Sports tape was used to avoid cluttered wires.

Figure 31: An isotonic recording gel strengthens the signals.

Before the participants began on the tasks, they were told to move their arm, hand, and fingers to control the instruments' responses. The *Biopac Student Lab* software would then show whether or not the electrodes responded to the muscle contractions.

Task Performance

The participant was given the tasks in a randomized order. The underlying intention of the tasks was unknown to the participant to avoid participant biases in the determination of perceived exertion. All the tasks had 20 aimed targets, and the participant had to perform them one-handed without the support of a second hand, table, etc. When all the twenty targets for each condition were tapped by the participant, a finished screen appeared, as shown in Figure 32.

Done!

Figure 32: The finish screen.

Breaks and Determination of Perceived Exertion

There were 2-minutes breaks between each task. The breaks were measured with a timer software. The breaks also let the participants recover for the next task, as an attempt to avoid fatigue and biased EMG data. This was vital for the experiment, as fatigue is one of the challenges of a within-group design (Lazar, Feng&Hochheiser 2010). During the 2-minute breaks, the participants were told to determine the perceived exertion following the Borg Scale when the perception still was clear in their minds. The participants were allowed to change the rate of perceived exertion by the end of all tasks, as they then would have a better basis of comparison. This data would later be compared to the objective indexes from the EMG.

The Borg Scale

The Borg Scale measures user perceived exertion during a physical test and was introduced by the Swedish psychologist, Gunnar A. V. Borg. The Borg Scale was developed as a method to quantify subjective symptoms in health care, as it is a common agreement among scientists that subjective symptoms are important to understand objective findings. The Borg Scale can be applied to nearly all people, independent of gender, age, circumstances, and national origin (Borg 1982). This research applied the Borg CR10 Scale, which is an 11-grade (0–10) type of Borg Scale. The Borg CR10 Scale was in this case used to document discomfort in terms of smartphone tasks. The applied Borg CR10 Scale was printed and placed on the table in front of the participant. The scale was as follows (Borg 1982, p. 380):

0	Nothing at all	
0.5	Very, very weak	(just noticeable)
1	Very weak	
2	Weak	(light)
3	Moderate	
4	Somewhat strong	(heavy)
5	Strong	
6		
7	Very strong	
8		
9		
10	Very, very strong	(almost max)
•	Maximal	

Figure 33: The Borg CR10 Scale.

Processing of Raw Data

After each conduction had been completed, a data file was saved for the participant. A root mean square (RMS) at 100 samples was derived from the raw data. An RMS is defined as a root of the mean of the squares of a data sample, and the output is a continuous waveform. It makes the data easier to analyze. Moreover, RMS is a frequently chosen parameter in scientific analysis because it well reflects the levels of muscle activities while resting and during contraction (Fukuda et al. 2010). Figure 34 shows an example of the raw EMG data while Figure 35 shows an RMS derivation of the same set of data.

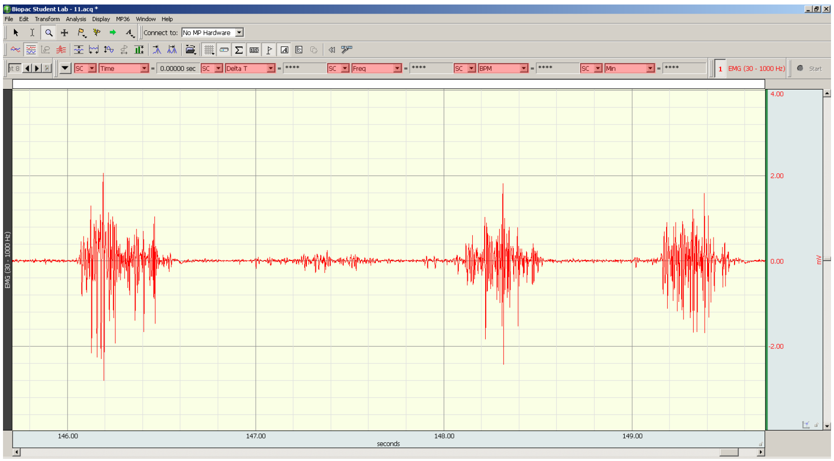


Figure 34: Raw EMG data.

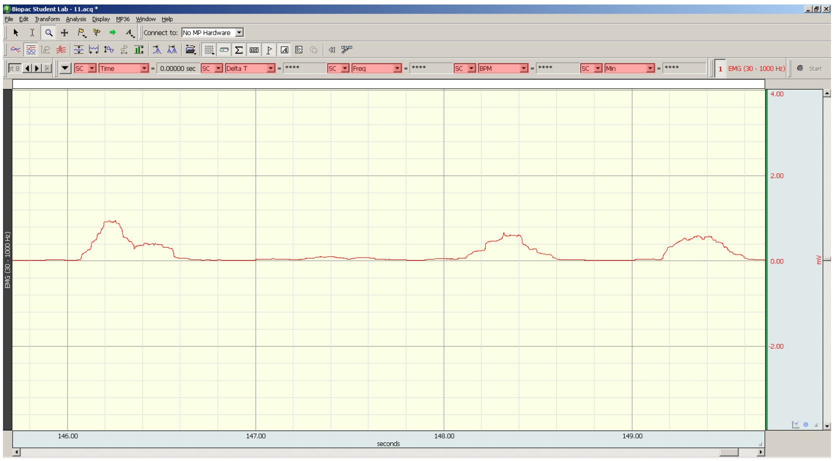


Figure 35: RMS Derivation.

4 Results

This chapter presents the results from the two types of research conducted in this master thesis. Section 4.1 presents the results from the expert interviews. Section 4.2 presents the results from the EMG test, which is considered to be the main research in this master thesis.

4.1 Results from the Expert Interviews

The expert interviews addressed the topic of RSI, smartphones, the human physiology, and the ergonomics of digital systems. Content analysis was applied to analyze the interview data. Eight physiotherapists (six male; two female) were recruited. All were familiar with RSI, its causes and symptoms, and did physiotherapy for a living. They all had experiences with patients who suffered from RSI.

Six out of eight interviewees reported that they have had many patients with RSI symptoms from computer and smartphone usage. RSI symptoms from primarily smartphone usage were less common, as only one of the physiotherapists reported about patients who suffered from smartphone related injuries alone. This was caused by a mobile game. However, one interviewee responded the following to a question about the differences of RSI between computer and smartphone usage:

"Personer som sitter mye på PC sitter også ofte mye med mobil. Noe som gjør det vanskelig å differensiere mellom frekvens, skadeområde og grunn til skade."[3]

Six out of eight interviewees reported that the thumb is the muscle that is prone to injuries when overusing a smartphone. This is due to small, repetitive movements. Two of the interviewees went in detail by telling that the combination of static (holding the device with the hand) and dynamic work (tapping with the thumb) was a harmful operation technique. It was also reported that the neck, shoulders, wrists, and back are prone to injuries.

Common conceptions were that existing mobile, digital solutions are not good for the health, five interviewees reported. Furthermore, the physiotherapists were presented an estimated

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[3] Translated into English: *"People who sit a lot at a computer most often also use a smartphone frequently. This makes it hard to differentiate between frequency, damaged area, and cause of the injury."*

functional area for the iPhone 6 made by Scott Hurff (2014), which was published on his design blog. The presented model follows the same basics as Luke Wroblewski's (2011) design suggestions and Bergstrom-Lehtovirta and Oulasvirta's (2014) scientific formula for the functional area. Five of the physiotherapists reacted positively to the principle of the functional area for one-handed interaction. One of the interviewee also commented that the presented functional area, shown in Figure 36, did not pay attention to left-handed users.

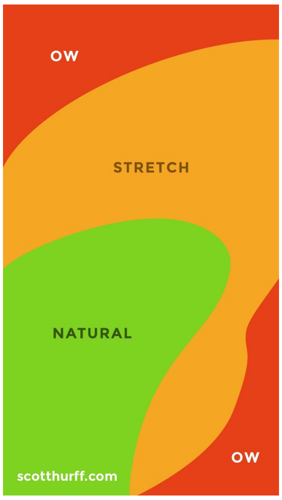

Figure 36: The presented functional area. Source: Scott Hurff (2014)

Another common conception, stated by four of the interviewees, is that the introduction of smartphones was the time when phone related RSI symptoms began. As explained by one of the interviewees when asked when phone related RSI symptoms occured:

“Hvis jeg skal komme med hypotese må det være ved smarttelefonenes inntog hvor vi ble mindre avhengige av PC. Mobil dekker mange av de behovene som PC tidligere var alene om.”[4]

Four of the interviewees stated that large smartphones are more prone to RSI symptoms because they are heavier to hold. However, one of them also mentioned that thin smartphones also have negative consequences because it forces the user to grip the smartphone harder. Two interviewees mentioned that high tapping precision is not good for the human musculoskeletal system.

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[4] Translated into English: *“If I had to come with a hypothesis, it must be with the entry of the smartphones that made us less dependent of computers. Mobiles cover many of the needs that earlier were exclusively for computers.”*

4.1.1 Basis for Hypotheses

The current smartphone GUIs force us to stretch our thumb to uncomfortable extents. By applying the principles of the functional area into the user interface, the design can be more ergonomic. Right-handed and left-handed users need different user interface layouts for ergonomic purposes. It is possible that touch key sizes affect the extent of generated muscle contraction.

4.2 Results from the EMG Test

The EMG test examined the following hypotheses made from the interview data:

1. Touch keys inside the functional area expose less muscle contraction than touch keys outside the functional area.
2. A GUI designed for the user's preferred hand exposes less muscle contraction than a GUI not designed for the user's preferred hand.
3. Large touch key sizes expose less muscle contraction than small touch key sizes.

11 participants (six male; five female; age 23–26) were recruited to the study. The target group was the same as in the pre-study, as 88% of the participants reported that they prefer to interact one-handed with a smartphone. One was left-handed. None suffered from RSI. The participants' thumb length was between 114 mm–139 mm (mean length at 130 mm), and hand length between 166 mm–196 mm (mean length at 184 mm). All participants owned a touchscreen smartphone.

Since physiological responses are individual (Bloom et al. 1976; Hautala et al. 2006), each participant went through all the six different conditions. Individual differences in muscle recording would therefore not affect the overall results. The values of muscle contractions from each participant were combined before the analysis. The muscle contractions were measured in millivolt (mV). The data analyzed is the total sum of all the 11 participants.

An RMS was derived to the raw EMG data to make it easier analyzable. The data was analyzed through SPSS for OS X. The analysis applied two different statistical methods for different purposes: *paired-samples t tests*, and *multiple-level, repeated measures ANOVA*.

Paired-samples t tests are appropriate to compare two different conditions, performed by the same group of participants. It was applied to the first and second hypotheses. Multiple-level, repeated measured ANOVA is appropriated for empirical studies with a within-group design, consisting of two or more conditions. It was applied to the third hypothesis.

Following abbreviations are applied in this section to refer to the different conditions:

FAD	*functional area, dominant hand*
FAN	*functional area, non-dominant hand*
UL	*unergonomic layout*
TKS	*small touch key size; 7 mm*
TKM	*medium touch key size; 10 mm*
TKL	*large touch key size; 13 mm*

4.2.1 First Hypothesis

There were three study tasks dedicated to examining the first hypothesis:

Task 4: **Ergonomic touch key locations intended for left-handed users**
Task 5: **Ergonomic touch key locations intended for right-handed users**
Task 6: **Unergonomic touch key locations**

Task 4 and 5 applied an estimated functional area for respectively left-handed and right-handed users. As these two tasks depended on the participant's operating hand, two new variables were created for the analysis process: "Functional area, dominant" (FAD) and "functional area, non-dominant" (FAN). These variables took the participant's dominant and non-dominant hand into account and selected one of the two layouts for each variable. All 11 participants were therefore included in both variables.

Two paired-samples t tests were applied in order to investigate the first hypothesis. The comparisons were as follows: FAD vs. UL, and FAN vs. UL

The mean value of FAD vs. UL show that FAD does not lead to any statistically significant decline ($t = 0.457$, $P > 0.05$) in muscle contractions. When comparing FAN to UL, the results show that the mean value of FAN gives a statistically significant decline ($t = -2.624$, $P < 0.05$) in muscle contractions compared to UL.

4.2.2 Second Hypothesis

There were two study tasks made to examine the second hypothesis:

Task 4: **Ergonomic touch key locations intended for left-handed users**
Task 5: **Ergonomic touch key locations intended for right-handed users**

Similar to the analyzing process of the first hypothesis, the variables "Functional area, dominant" (FAD) and "functional area, non-dominant" (FAN) were applied to this analysis process. FAD takes into account the participant's dominant hand; FAN takes into account the participant's non-dominant hand. A paired-samples t test was performed in order to investigate if whether the two visually mirrored layouts affected the physiological responses differently.

The mean value of FAN shows a decline in muscle contractions close to statistically significant ($t = -2.219$, $P = 0.051$) compared to FAD. The sum of the muscle contractions, however, is statistically significant lower ($t = -2.234$, $P < 0.05$) for FAN than FAD. Figure 37 shows the mean values of all the three tasks dedicated to the first and second hypotheses.

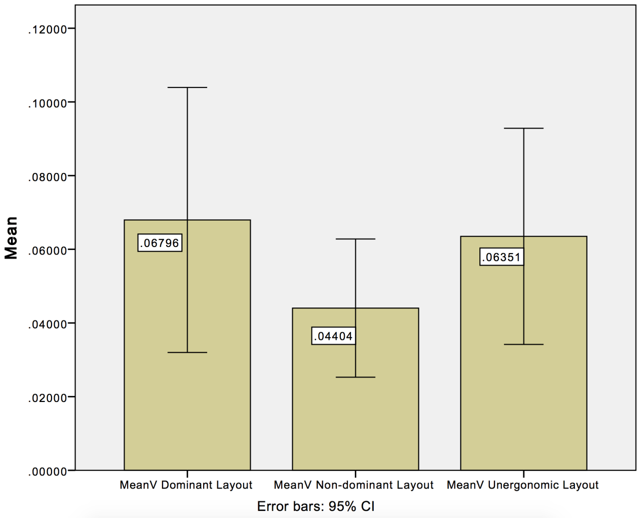

Figure 37: Mean values of FAD, FAN, and UL.

4.2.3 Third Hypothesis

There were three study tasks dedicated to examining the third hypothesis:

Task 1: **Small touch key size (7 mm) [TKS]**
Task 2: **Medium touch key size (10 mm) [TKM]**
Task 3: **Large touch key size (13 mm) [TKL]**

All these three tasks had the identical touch key positions and were spread over the whole screen area, without following a specifically given area. The only difference was the touch key size. To analyze the results, a multiple-level, repeated measures ANOVA was applied to the mean values of the tasks.

The mean values did not show any significant differences in muscle contraction between TKS, TKM, and TKL. TKM was, however, slightly higher than the other two. Figure 38 shows the mean values of the respective tasks.

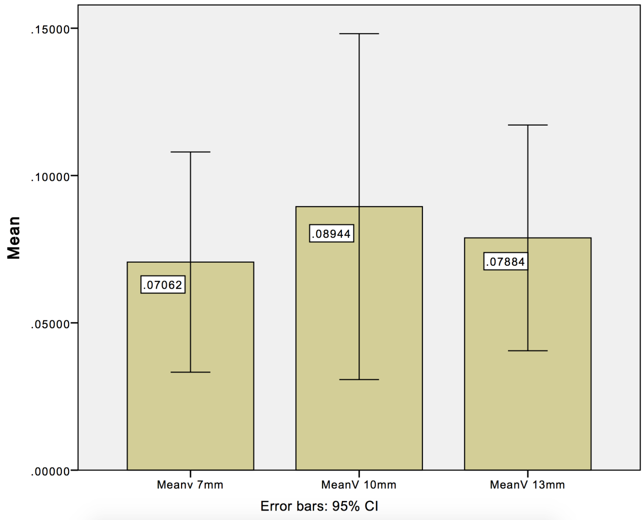

Figure 38: Mean values of TKS, TKM, and TKL.

4.2.4 Borg Scale

The EMG test also tracked the participants' subjective perceived exertion by use of the Borg Scale, to compare it to an objective index, from the EMG data. The applied Borg Scale, called the "Borg CR10 Scale," is an 11-grade scale, ranging from 0–10. These values were determined by the participants during the task breaks.

As the EMG data shows statistically significant differences between FAN and UL, and FAN and FAD, paired-samples t tests were performed to the same conditions of the Borg Scale statistics. Moreover, a descriptive statistics test was performed on all the tasks.

When comparing the Borg Scale statistics of FAD and FAN to the UL, both of FAD and FAN were statistically significant better perceived than UL ($P < 0.05$). In contrast, the EMG data shows that only FAN generates statistically significant less muscle contractions than UL. When comparing the Borg Scale data of FAN to FAD, there are no statistically significant ($P > 0.05$) results that the participants perceive FAN more comfortable than FAD. However, the EMG data shows that FAN has a statistically significant decline in muscle contractions compared to FAD.

The descriptive statistics test shows that the mean value was lowest on FAN. The highest values are found on UL and TKM. TKS, TKM, and TKL, which examine different touch key sizes, were all perceived very similarly. TKS, TKM, and TKL were perceived as more uncomfortable than FAN and FAD. Figure 39 shows a graphical summary of the mean values of the Borg Scale results.

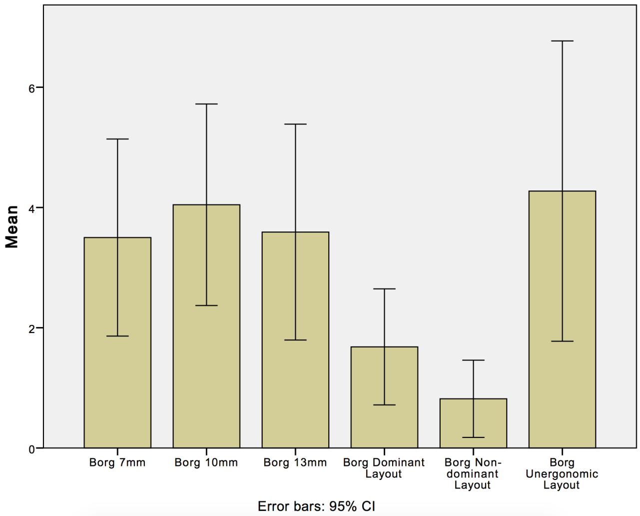

Figure 39: Mean values of the Borg Scale results.

5 Discussion

This chapter discusses the results and data collected in this master thesis. Moreover, it discusses the two research questions presented in chapter 1.2. Finally, a suggestion of an ergonomic user interface guideline is presented. The suggestion is intended for one-handed interaction. The guideline was designed from the collected EMG data.

5.1 Expert Interviews

RSI symptoms are widespread these days. A common factor for RSI symptoms is the combination of computer and smartphone usage. Use of these technical devices strains the muscles due to rapid, repetitive movements. Exaggerated use may lead to pains and injuries. People are especially exposed to RSI now as smartphones have become pocket computers and are easily carried. The prone to RSI is higher today as the smartphones have become so large that they are heavy to hold, and more difficult to operate one-handed.

Even if only one physiotherapist reported about patients who suffered from smartphone injuries, there were general agreements that RSI symptoms most often come from a combination of computer and smartphone usage. As one of the physiotherapists stated, it is often a correlation between heavy use of computers and smartphones. The explanation could be that smartphones have become pocket computers, capable of doing computer tasks, such as accessing the Web, email, social networks, etc. It is also normal to use different portable devices—such as smartphones, tablets, and laptops—interchangeably, which makes it hard to find one single source of muscle issues (Stawarz&Benedyk 2013). However, it has been reported that overuse of smartphones alone also can develop critical RSI symptoms (Shim 2012).

Five interviewees considered the presented functional area logic. One of the physiotherapists commented that the presented functional area only is optimized for right-handed people:

"Venstrehendte vil jo da komme i rød sone hele tiden."[5]

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[5] Translated into English: *"Left-handed people will then come in red zone all the time."*

The results from the EMG test corresponds with the inputs from the physiotherapists. It shows that the principles of the functional area is ergonomically beneficial if designed properly for either hand. One single functional area is not ergonomically beneficial for both right-handed and left-handed users.

Two physiotherapists said that tasks that require high tapping precision could provide higher muscle contractions. As reported by Park and Han (2010b), small touch key sizes (4 mm) provide higher error rates than large touch key sizes (7 mm and 10 mm). The EMG results do, however, not show any significant differences in muscle contraction between small, medium, and large touch key sizes.

5.2 EMG Test

Hypothesis 1: Touch keys inside the functional area expose less muscle contraction than touch keys outside the functional area.
The EMG data shows that there are statistically significant differences in muscle contraction between GUIs based on the functional area compared to the unergonomic area. However, the results show that the functional area exposes statistically significant less muscle contraction than the unergonomic area only if it is *properly* designed for the user's specific dominant hand. The results of the Borg Scale also showed that the two tasks consisting of the functional areas were subjectively perceived as the most comfortable. The first hypothesis is confirmed.

Hypothesis 2: A GUI designed for the user's preferred hand exposes less muscle contraction than a GUI not designed for the user's preferred hand.
The data shows that a GUI designed for a user's preferred hand nearly exposes statistically significant less muscle contraction than a GUI designed for the user's non-preferred hand. Paradoxically, in this case, task 4, which was intended for left-handed users, is best suitable for right-handed users. In contrast, task 5, which was intended for right-handed users, is best suitable for left-handed users. The results of the Borg Scale also showed the same results as the EMG data: Users found either of the layouts more comfortable than the other depending on their dominant hand. Even if the two functional areas applied to the EMG test had reversed effects, the second hypothesis is confirmed.

Hypothesis 3: Large touch key sizes expose less muscle contraction than small touch key sizes.

There were no clear differences in the level of muscle contraction between the different touch key sizes, on respectively 7 mm, 10 mm, and 13 mm. The results of the Borg Scale on these three tasks corresponded to the EMG data. The data outcome from this test cannot confirm the third hypothesis.

EMG Data vs. Borg Scale

The Borg Scale statistics correspond mostly with the EMG data, which indicates that EMG is a valid type of measurement to investigate ergonomic factors. However, the EMG data shows that the "functional area, dominant" does not statistically significant generate less muscle contractions than the "unergonomic area". The Borg Scale statistics, in contrast, shows that it does.

5.3 First Research Question

Which factors affect the ergonomics of user interfaces on large smartphones?

5.3.1 The Functional Area

The results show that there is a correlation between different touch key positions and the amount of muscle contraction generated. This was as expected, as various touch key positions make the user extend the thumb differently. Furthermore, the results also show that the estimated functional area works well in terms of declining the level of generated muscle contractions, but only if the area is properly estimated for the user's operating hand. In the case of the conducted EMG test, the two different functional areas for left-handed and right-handed users were improperly designed. The right-handed functional area was a model made by Scott Hurff (2014), while the left-handed functional area was simply the same model, but visually mirrored. The results were paradoxical: The functional area intended for left-handed people generated the lowest level of muscle contraction for right-handed people, and vice versa. The EMG data show that there are no statistically significant effect by having an improperly estimated functional area. In fact, the data show that an improper functional area even made the user generate a higher level of muscle contraction than the layout that was designed to be the less ergonomic.

By calculating the mean values of all the ten right-handed participants, performed on the layout that initially was designed for right-handed users, the value was 0.7395 mV. The mean value of the same ten participants performed on the layout that was designed to be the least ergonomic, was 0.6889 mV. When looking at the mean value performed on the layout that was designed for left-handed people, the result is 0.4765 mV. Figure 40 shows the mean value of muscle contraction performed by ten right-handed participants, on three different layouts during the EMG test. The y-axis shows the muscle contraction value, measured in mV, while the different layouts are shown in the x-axis. The different layouts are simply called "Layout 1" (which was task 5), "Layout 2" (which was task 6), and "Layout 3" (which was task 4) to avoid misconceptions regarding the paradoxical results from the EMG test.

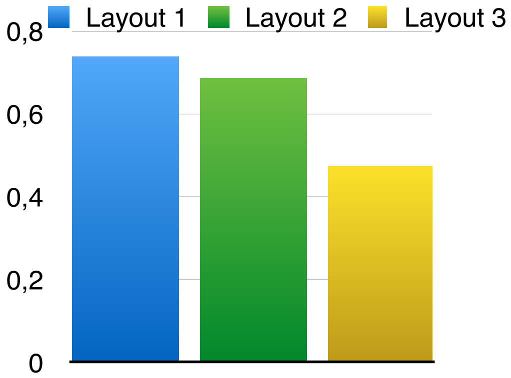

Figure 40: Mean value of muscle contraction performed by ten right-handed participants.

The EMG test showed that Figure 41—that was initially designed for left-handed users—is the most ergonomic layout for right-handed users. Figure 42—that was initially designed for right-handed users—is the most ergonomic layout for left-handed users. Thus, the principles of the functional area can positively affect the ergonomics of a mobile user interface, only if it is designed properly for the user's dominant hand.

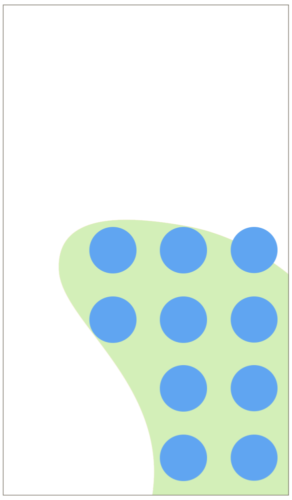

Figure 41: Most ergonomic for right-handed users.

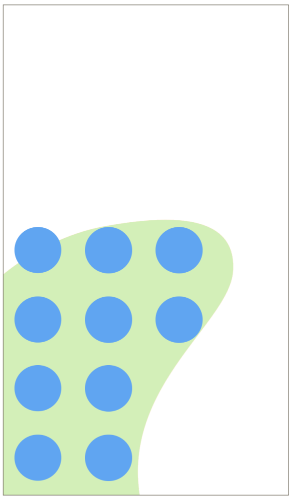

Figure 42: Most ergonomic for left-handed users.

The findings from this study do not fully correspond to the functional area illustrated in Luke Wroblewski's (2011) literature, *Mobile First*. Wroblewski focuses specifically on right-handed people since the majority of people is right-handed. Figure 43 was used as an illustrative example in Wroblewski's book, as how a functional area for right-handed people would look like (Wroblewski 2011, p. 73): "While holding a touch screen phone with only your right hand, it's easy to hit the dark green area […]". However, the EMG data from this master thesis indicates that the most comfortable area to hit, for right-handed users, is when the functional area is placed on the edge of the right side of the screen. According to the results from this study, Luke Wroblewski's suggestion is more comfortable for left-handed users. Moreover, Scott Hurff's (2014) functional area designed specifically for the iPhone 6, which was applied to the EMG tasks, does also not correspond to the results of this study. Scott Hurff designed the functional area, shown in Figure 44, specifically for right-handed users. As the results of the EMG test show paradoxical results between the estimated functional area for right-handed and left-handed people, Steve Hurff's functional area is assumed to be improper. It is most ergonomic for *left-handed* users. Moreover, Bergstrom-Lehtovirta and Oulasvirta (2014), the researchers behind a formula to predict the functional area of the thumb, state in their study that designers have long made heuristics to estimate the functional area, but that these estimations are rough. However, this study shows that the existing heuristics can even lead to a worse ergonomic.

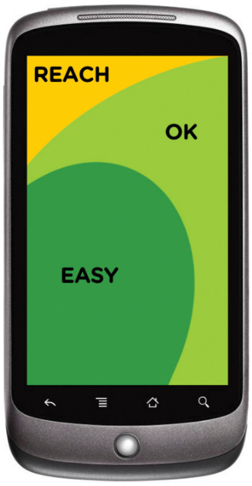

Figure 43: An example of the functional made by Luke Wroblewski (2011, p. 73).

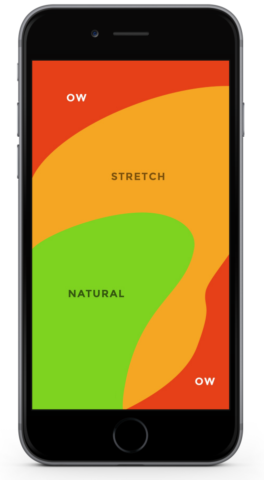

Figure 44: An estimated functional area for the iPhone 6 made by Scott Hurff (2014).

5.3.2 User Interface Optimization for Dominant Hand

It was hypothesized that a user interface designed specifically for either hand would positively affect the ergonomics. Since the left and right hand are the opposite of each other, it was expected that a visual mirroring of a GUI designed for one hand, would make it more ergonomic for the other hand. In the analysis of the EMG data, there were created two variables for the two mirrored functional areas: one for the dominant hand, and one for the non-dominant hand. This made it possible to include all the eleven participants in the analysis of the two different layouts, independent of whether they were left-handed or right-handed. The results from the data analysis show clear differences in muscle contraction between the functional areas made for different hands. By comparing the two different layouts, the mean value of muscle contraction is marginal to a statistically significant difference ($t = -2.219$, $P = 0.051$). A p-value at 0.051 is by definition not statistical significant as the confidence level was set to 95%, but one could argue that the extra 0.001 is negligible, thus it is a clear tendency for significant results. However, the difference in the sum of muscle contraction was statistically significant ($t = -2.234$, $P < 0.05$). The results show that simply mirroring a user interface, visually, give significant differences in muscle contraction.

Perry and Hourcade (2008) reported that the performance level between using a dominant hand to a non-dominant hand is large enough to evaluate a GUI for both hands. They found that approximately a third of students from a few classes at their university sometimes use their non-preferred hand to interact with their smartphones. One of the reasons was due to an occupied dominant hand. A simple customization setting to move the primary actions to the other side of the smartphone screen would therefore be beneficial, both for the performance and the ergonomics.

5.3.3 Touch Key Size

It was expected that different touch key sizes affect the level of muscle contractions. Park and Han's (2010b) study about touch key locations and touch key sizes show that task completion time and numbers of errors increased as the touch key size decreased. However, their study did not take ergonomical aspects into account. One of the hypotheses for the EMG test was therefore that the negative usability aspects from a decrease of touch key size, as reported by Park and Han (2010b), also affected the ergonomics negatively.

The EMG data from the eleven participants did not show any clear differences in muscle contraction between small, medium and large touch key sizes—respectively 7 mm, 10 mm and 13 mm, as shown in Figure 45. An explanation could be that users mostly tap the center of the targets, independent of whether it is 7 mm, 10 mm or 13 mm. This makes the tapping target near identical in all three touch key sizes. Moreover, it could be that small touch key sizes only affect factors like numbers of errors and pressing convenience, but not directly on the extent of muscle contraction. One could argue that a high error rate and low pressing convenience would lead to unnecessary, redundant taps, which in the long term could give a significant effect on the total muscle contraction. The EMG test from this study did, however, not show any significant effects between the different touch key sizes.

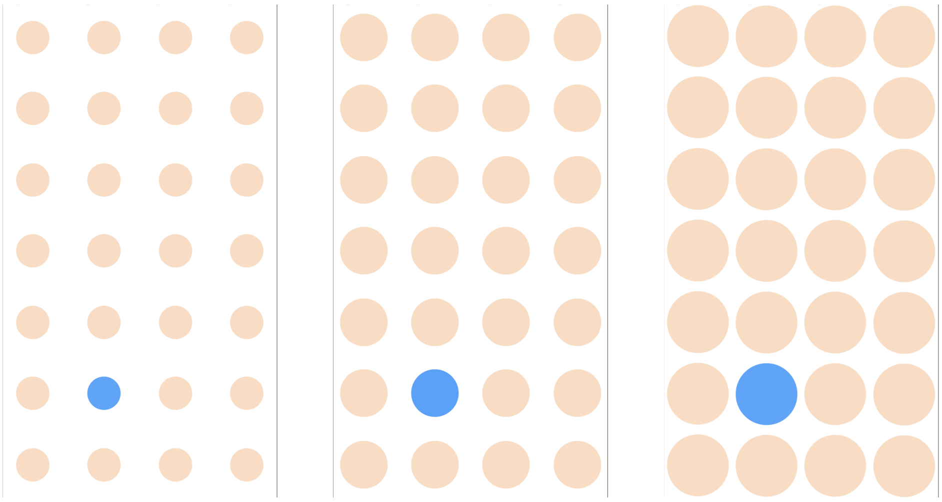

Figure 45: 7 mm (left), 10 mm (middle), and 13 mm (right) touch key sizes.

To further analyze the differences between the touch key sizes, descriptive statistics were performed on six randomly assigned participants, from the total 11. The intention was to control if a randomly assigned analysis of half of the participants would give different results. The results still show little differences in the mean values of muscle contraction. The third hypothesis about the correlation between touch key sizes and level of muscle contraction is therefore rejected.

5.4 Second Research Question

To what extent will a user interface design that takes the functional area into account, improve the ergonomics of large smartphones?

The EMG data shows that by applying the principles of the functional area into a user interface, the level of muscle contractions can statistically significant decline. The results of the Borg Scale also show statistically significant differences between the two different functional areas and the unergonomic layout. However, the results from the Borg Scale show that the participants found both of the functional areas more comfortable than the unergonomic layout. The EMG data, in contrast, shows that only one of the functional areas provide less muscle contraction during use, depending on the user's dominant hand. Both the EMG data and the Borg Scale support that a user interface that takes the functional area into account can improve the ergonomics of large smartphones.

It is hard to determine the extent of increased ergonomics of large smartphones by applying the principles of the functional area into the user interface. Musculoskeletal issues and RSI are complexed phenomenons, but one could get some insights by looking at the statistics and causes for these injuries. RSI has grown steadily during the last decades in a number of countries, including USA, UK, Norway, and Japan. Some factors that are risky for RSI are repetitive motions, static movements, and bad postures (Yassi 1997). Especially computer users are prone to RSI (Keller, Corbett&Nichols 1998; Jensen et al. 2002). However, newer studies have proven that all kind of mobile devices have a negative effect on the human musculoskeletal system (Bachynskyi et al. 2015). This is problematic as we, in this part of the world, rely strongly on our mobile devices. 60% of online traffic comes from mobile devices (Lipsman 2014), which indicates the massive growth of mobile platforms in the past few years. Overuse of smartphones can even develop musculoskeletal issues like carpal tunnel syndrome (Shim 2012). It is, therefore, important to be aware of the fact that smartphone usage also poses a risk for RSI.

As RSI comes from repetitive motions over an extended time, one would believe that a slight decrease in muscle contraction during each movement has an ergonomic effect. A study by Aarås et al. (2001) reported that computer workers who already suffered from pain experienced significantly reduced pain in certain body parts by changing to a more ergonomic computer mouse. These findings support that a change in input device can improve the ergonomics of the computer interaction. It is, therefore, natural to believe that a change in user interface design could have the same benefits. By comparing the mean values of muscle contraction from "the functional area, dominant" to "the functional area, non-dominant" applied to the EMG test, the differences are 54% (0.06796 mV; 0.04404 mV). One could argue that a user interface that takes a proper functional area into account could, in the long term, have a substantial ergonomic effect.

5.5 Weaknesses of the Study

The study did not pay attention to how the participants were holding the phone. To get the most out from the functional area applied to the EMG test, the user must hold the phone so the bottom line of it is on par with the little finger of the holding hand. If the user uses a higher grip, the applied functional area will be further away than intended.

Some participants reported that the electrode wires and the sports tape attached to the hand felt unnatural. Some of them also found the electrode wires and sports tape disturbing for the thumb movements, making it slightly harder to move around the thumb. The electrodes were, however, necessary for the EMG to work. The sports tape was used to avoid a cluttered set-up.

There was only one left-handed participant in the EMG test. More left-handed participants would have been beneficial for this study, as the differences between the muscle contractions of left-handed and right-handed users were in focus.

A laboratory setting can be an unnatural way to study human—computer interaction. This is a challenge in human—computer interaction research as laboratory conditions do not fully allow the researcher to understand all the variables involved. Ben Shneiderman (2008) uses the terms "Science 1.0" and "Science 2.0". Science 1.0 is the traditionally research strategies including hypothesis testing, predictive models, and validity. Science 2.0, in contrast, is the science about the relation between people and technology, *human—computer interaction*, where real settings are most beneficial.

5.6 Suggestion for a User Interface Guideline

This section presents a suggestion for a new user interface layout from the collected data in this master thesis, shown in Figure 46. The user interface guideline focuses on an ergonomic solution for one-handed interaction, intended for mobile devices with a 4.5–5" screen. It is designed in two different versions, for both right-handed and left-handed users. These two versions are simply a visual mirroring of one another. The guideline suggests that users can switch between the two different versions from the settings panel. The user interface would, therefore, benefit the users ergonomically independent of their dominant hand. The upper field of the screen is recommended to be used for destructive actions, as suggested by Luke Wroblewski (2011). Destructive actions are, for instance, cancel and delete. By keeping this type of actions away from the functional area, it will be harder to perform a destructive action by accident. Lastly, as the data collected in this master thesis is specifically for one-handed interaction, it is suggested that the following user interface layout is implemented as a dedicated mode. The mode can be activated with a toggle button in a quick settings panel (for instance *Control Center* in iOS or *Quick Settings* in Android). This gives the user easy access to activate and deactivate the one-handed layout.

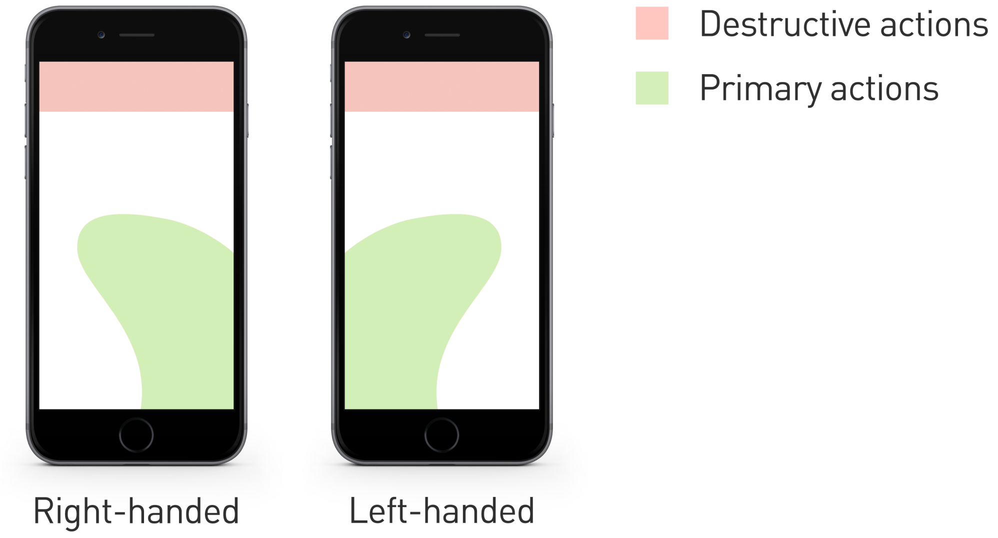

Figure 46: Suggestion for a user interface guideline.

6 Conclusion

As RSI has increased steadily during the last decades, it is important that designers take ergonomic factors into account when designing user interfaces. This master thesis has investigated the relation between different touch key locations, touch key sizes, and the functional area, to the ergonomics of one-handed smartphone interaction. The investigation consisted of expert interviews and an EMG test.

The results of the study show a significant correlation between a user interface that applies the functional area and a decline in muscle contraction. The decline in muscle contraction only occurs if the functional area is designed specifically for the user's dominant hand. This shows the importance of designing a user interface for both right-handed and left-handed users. The results did, however, not show any significant correlations between different touch key sizes and the extent of generated muscle contraction.

The findings from this study show that current mobile OSes have room for improvements in terms of one-handed interaction. As the user interfaces of iOS and Android are designed for small screens, it affects the ergonomics negatively when interacting on a large smartphone one-handed. The results from the pre-study show that iOS clearly is most preferred on small devices when interacting with one hand.

This study has shown that the design of a mobile user interface can affect the ergonomics of the interaction. The results support the idea of the functional area as it has been shown to positively affect the ergonomic of a one-handed interaction of large smartphones. As most people prefer to interact one-handed with their mobile devices, a new user interface layout has been suggested for a more ergonomic user experience. The user interface layout was designed from the findings of this master thesis.

6.1 Future Work

User interface designers have long been aware that touch key locations and touch key sizes have an impact on the time it takes to hit a target area, known as *Fitts' law*. Fitts' law is a mathematic model of speed-accuracy widely used in human—computer interaction, originally proposed by Paul Fitts in 1954 (Fitts 1954). It predicts that large touch keys at a close range is faster to hit than small touch keys at a long range. As products with multi-touch interfaces have grown largely during the last decade, future work could focus on the ergonomic effect of different touch key locations and touch key sizes. Research on user interface design and the potential musculoskeletal issues provided is necessary to improve the current health issues in the society caused by static, repetitive work. With time, future research could come with detailed knowledge about the relation between touch key locations and touch key sizes and the provided physiological responses. Researchers might even discover a predictive model, such as Fitts' law can predict speed-accuracy.

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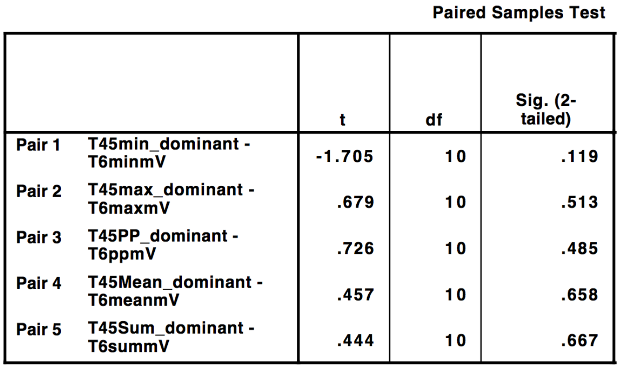
Appendix A: Statistical Analysis

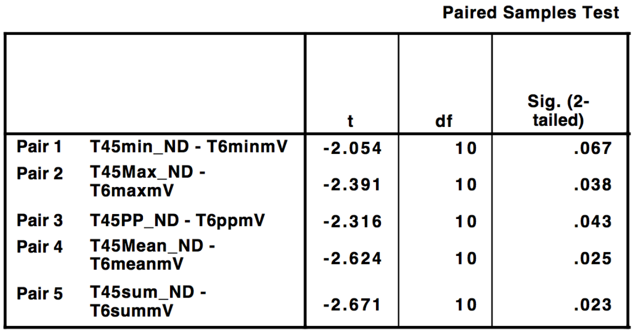
Functional area, dominant vs. unergonomic area:



Paired Samples Test

		t	df	Sig. (2-tailed)
Pair 1	T45min_dominant - T6minmV	-1.705	10	.119
Pair 2	T45max_dominant - T6maxmV	.679	10	.513
Pair 3	T45PP_dominant - T6ppmV	.726	10	.485
Pair 4	T45Mean_dominant - T6meanmV	.457	10	.658
Pair 5	T45Sum_dominant - T6summV	.444	10	.667

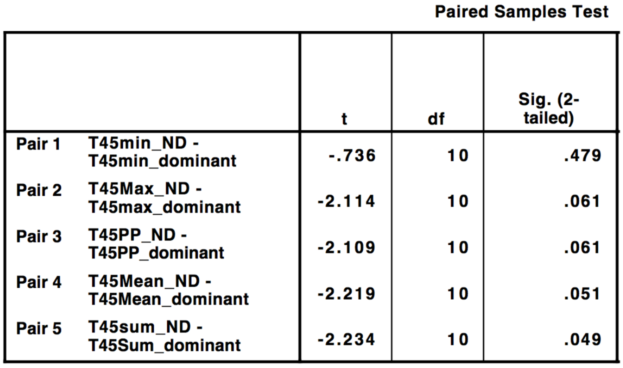
Functional area, non-dominant vs. unergonomic area:



Paired Samples Test

		t	df	Sig. (2-tailed)
Pair 1	T45min_ND - T6minmV	-2.054	10	.067
Pair 2	T45Max_ND - T6maxmV	-2.391	10	.038
Pair 3	T45PP_ND - T6ppmV	-2.316	10	.043
Pair 4	T45Mean_ND - T6meanmV	-2.624	10	.025
Pair 5	T45sum_ND - T6summV	-2.671	10	.023

Functional area, non-dominant vs. functional area, dominant:



Paired Samples Test

		t	df	Sig. (2-tailed)
Pair 1	T45min_ND - T45min_dominant	-.736	10	.479
Pair 2	T45Max_ND - T45max_dominant	-2.114	10	.061
Pair 3	T45PP_ND - T45PP_dominant	-2.109	10	.061
Pair 4	T45Mean_ND - T45Mean_dominant	-2.219	10	.051
Pair 5	T45sum_ND - T45Sum_dominant	-2.234	10	.049

Descriptive statistics:

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
T1meanmV	11	.00870	.15830	.0706218	.05563321
T2meanmV	11	.00834	.31429	.0894436	.08737590
T3meanmV	11	.01246	.19966	.0788391	.05702532
T4meanmV	11	.00805	.09642	.0440482	.02790491
T5meanmV	11	.00791	.18599	.0679464	.05355454
T45Mean_dominant	11	.00805	.18599	.0679591	.05353886
T45Mean_ND	11	.00791	.09642	.0440355	.02792300
T6meanmV	11	.00969	.13404	.0635091	.04366522
Valid N (listwise)	11				

Borg Scale:

Paired Samples Test

		df	Sig. (2-tailed)
Pair 1	T45Borg_dominant - T6Borg	10	.037
Pair 2	T45Borg_ND - T6Borg	10	.018
Pair 3	T45Borg_ND - T45Borg_dominant	10	.109

Statistics

		T1Borg	T2Borg	T3Borg	T45Borg_dominant	T45Borg_ND	T6Borg
N	Valid	11	11	11	11	11	11
	Missing	0	0	0	0	0	0
Mean		3.500	4.045	3.591	1.6818	.8182	4.273
Median		3.000	4.000	4.000	2.0000	.5000	3.000
Std. Deviation		2.4393	2.4945	2.6722	1.43654	.95584	3.7173

Appendix B: Interview Questions

Hvor stor andel pasienter har du hatt med skader relatert til mobil- og PC-bruk? Hvordan har du behandlet dem?

Hva er forskjellene på å skade seg på PC-bruk og å skade seg på mobilbruk? Utdyp gjerne med frekvens, skadeområder, grunn til skade o.l.

Kan du fortelle litt om smerter i hender ved bruk av mobile enheter (gjerne om énhåndsbruk)? Hvordan det oppstår det? Hvilke typer skader oppstår? Hvor rammer det oftest?

Når begynte RSI-symptomer forårsaket av mobiltelefoner å oppstå?

Hvilke spesifikke muskler er det som slites mest pga. mobilbruk? Hvordan kan dette unngås, og hvordan kan designeren av et mobilt system ta hensyn til dette?

Hvordan synes du dagens mobile, digitale systemer tar hensyn til våre hender?

Hvordan blir dagens teknologi brukt generelt, i forhold til vår anatomi og potensielle skader? Hva er forskjellen på dagens bruk av muskulatur i motsetning til våre forfedre fra steinalderen?

Illustrasjonen ovenfor viser en estimering av et areal for komfortabel tommelbruk på en iPhone 6, med sin 4,7" skjerm. Hvilke anatomiske fordeler får man om illustrasjonen tas hensyn til i designprosessen?

Statistikk viser at det er svært mange som pådrar seg RSI i vårt moderne samfunn. Om vi derimot går tilbake i tid, da mange arbeidere jobbet på skrivemaskiner – som i utgangspunktet er mer belastende enn dagens tastaturer – var det allikevel sjeldent med RSI-symptomer i forhold til i dag. Hva er grunnen til dette?

Appendix C: Inform Consent

Informed Consent

Background
Smartphones are today used for a wide variety of tasks, including accessing the Internet, e-mails, music, photos, maps, and games—in addition to the traditional phone functionalities. It has cannibalized the sales of products like point-and-shoot cameras and GPS devices; it even has cut off the sales of PDAs and portable media players. Multi-touch smartphones have fundamentally become powerful pocket computers, and are frequently used in our society.

When operating mobile devices, most users prefer to interact with one hand. It is however challenging, as the major mobile OSes are not designed for one-handed interaction. There are certain areas of the screen that cannot be reached by the thumb when interacting with one hand. Touch keys far away from the thumb, for instance in the top corners of the screen, can for instance cause physical discomfort. Small, repetitive movements can in the long term even lead to musculoskeletal issues.

About the Experiment
This experiment focuses on different touch key locations and touch key sizes in a mobile GUI when operating a large smartphone one-handed. The differences in touch key locations and touch key sizes will be documented in terms of physiological responses, and the experiment will take use of electromyography (EMG). EMG is a technique used to measure muscle responses by detecting electric signals generated by the muscles.

Practical Information
The experiment consists of six (6) different tasks. These tasks have all different purposes for the experiment, but will be kept unknown for the participant. There will be 2 minutes breaks between each task. Estimated duration is approximately 30 minutes. There are no risks involved by participating, other than the potential discomfort generated by the smartphone operation. The participant's involvement, including the data outcome from the experiment, is kept anonymously and will not be used for other purposes than for this master thesis alone. All private data will be confidential. Participation is fully voluntary. The participant can withdraw from the experiment at any time, without any penalty or negative outcome.

If something is unclear, or if there are any questions about the experiment, feel free to ask.

Contact Information
Phone: 473 51 055
Email: phuong.nguyen@hig.no

Signature
By signing this consent form, the participant has understood the background and procedure of the experiment; that participation is voluntary; and withdrawal can be made at any time.

______________________________ ______________________________

Participant's signature *Date/location*