공학석사 학위논문

Effects of Grip Curvature and Hand Anthropometry for the Manual Operation of Handheld Touchscreen Device

소형 터치스크린의 한 손 사용에 대한 화면의 곡률과 손의 인체측정학적 요소의 영향에 관한 연구

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Abstract

To design handheld devices, physical comfort is one of the most crucial requirements. Recently, curved handheld touchscreens were released for enhancing comfort, but the effect has not been proved yet. There are two ergonomic factors, anthropometric and physiological factors, respecting comfort. This means the design should consider variation of hands in size and shape as well as muscle utilization. Through statistical analysis, it has been showed that the Korean population has large variability in both size and shape. Also, it has been observed that 1/3 of user population of smartphone operate the device unimanully by a previous research.

This study aimed to verify the effect of anthropometric factors of hands and curvature on comfort when using handheld touchscreen devices. Comfort level was measured employing both the subjective rating and EMG methods. Three mock-ups of handheld touchscreen device with different curvatures were utilized. One was flat device and the others had curvatures of 400R and 100R. An experiment was conducted on tapping, typing and dragging tasks. The results indicated that curvature of the handheld touchscreen devices did not affect muscle activities, but subjective comfort level. Moreover, size and shape of hand were found to affect muscle activities and comfort level when using the handheld touchscreen devices. Target location and moving direction of thumb were also factors that significantly affected muscle activities. Overall, this study suggests that user interface design may be more important than curvature of handheld touchscreen determining comfort of touch screen use.

Keywords: handheld touchscreens, curvature, comfort, EMG, user interface, thumb

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Chapter 1. Introduction

1.1 Research Background

Physical comfort is an essential requirement in product design. In particular, a wide of range of work-related instruments, from basic tools (e.g. Garden tool, hand saw) to electronic devices such as personal computer, has been concerned about comfort to increase productivity, safety and user satisfaction (Wickens, Gordon and Liu, 2004).

In order to enhance comfort, two factors should be considered: Anthropometric and physiological factors (Kolich, 2003). Anthropometry is the science dealing with body measurement connecting to working capacity. Ergonomics criteria related to anthropometry have long been considered a key aspect of comfortable use of product. The physiological factors deal with muscles, vertebral discs, and skin. In the cases related to muscles, the activities have been quantified using electromyography (EMG).

If discomfort feeling keeps for a long time, this will lead to impairment of efficiency and musculoskeletal disorders, both caused by muscle fatigue(Hollands and Wickens, 1999). Comfort for hands, same as other body parts, is major concern to prevent physical disorders.

In the occupational circumstances, employers have paid attention to the comfort in hand tools because uncomfortable devices result in

high risks of injury and low productivity (Kuijt-Evers et al., 2004). This issue has been extended from work places to everyday life; users prefer comfort personal electronic devices, for example keyboard, remote controller or mobile phone including touchscreens (Pheasant and Haslegrave, 2006).

Studies related to the touchscreen devices have been conducted to investigate physical, physiological and affective aspects of user interface and usability. Most of the researches associated with user interface were focused on the size of targets, the thumb envelope area or the location of targets from efficiency and effectiveness perspectives (Jin and Ji, 2010; Otten, Karn and Parsons, 2013; Perry and Hourcade, 2008; Sasangohar, MacKenzie and Scott, 2009), but not done much on the muscle activities of hands which is closely related to discomfort. Hand injuries and discomfort caused by frequent use of touchscreen smartphone definitely exist (Shim, 2012), but there is no clear design solution yet.

Meanwhile, curved touchscreens have been developed and just released to the market. The new types of the devices are expected to offer comfortable gripping, but this is a mere conjecture so far. Since few researchers have focused on the curvature of the touchscreen devices, the curved touchscreens do not guarantee to solve those problems.

1.2 Objective and Scope of the Study

In this study, the elements that affect comfort in unimanual operation for handheld device will be investigated. Firstly, size and shape of hands will be classified according to the hand anthropometric data representing Korean population. Having the result of the classification, the relationship between anthropometric factors of hand and comfort will be established in using three types of touchscreen smartphone mock-ups. The comfort level will be attained in both subjective and objective manners.

Participants will be determined by their shape and size of the hand and affiliated with the corresponding groups. The mock-up devices of touchscreen smartphone have different curvature: 400R, 100R and flat. The effect of curvature on comfort will be covered.

Objective comfort will be achieved by analyzing EMG signals. The EMG data will be collected while the participants perform three types of tasks with the mock-ups: tapping, dragging and typing. Determining the occurrence of muscle fatigue will be out of this study; quantifying muscle activities will be focused. Subjective rating will be collected after using each mock-up with the unidimensional scale for comfort. Lastly, the relationship between interface effect of target acquisition and thumb movement and the muscle activity will be investigated.

1.3 Definition and Terminology

Abbreviations and terms frequently used in this study and corresponding full-words are present in Table 1.

Table 1. Terminology and corresponding definition

Term	Full word
EMG	Electromyography
ADM	Abductor Digiti Minimi
OP	Opponens Pollicis
FDP	Flexor Digitorum Profundus
FPL	Flexor Pollicis Longus
MVC	Maximum Voluntary Contraction
%MVC	Ratio of maximum voluntary contraction
RMS	Root mean square amplitude of EMG signal
MEF	Median frequency
MSF	Mean spectral frequency

Chapter 2. Literature review

2.1 Comfort

2.1.1 The role of comfort in usability

According to Maslow(Maslow, 1943), there at least five basic needs, physiological, safety, love, esteem, and self-actualization, having a hierarchy prepotency. The first two needs are related to the minimum requirement retaining the lives, and next two needs are connected to psychological matter, for example, relationships with others and feeling of accomplishment. The last one is the ultimate desire achieving self-fulfillment. Human beings are motivated by these desires in different circumstances. This has been so called, Maslow's hierarchy pyramid and applied to a wide range of field. When designing a product, the contents are slightly modified as Figure 1 (Lidwell, Holden and Butler, 2010).

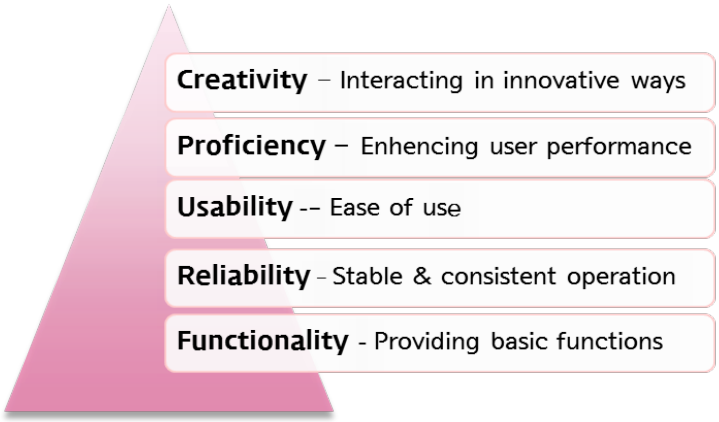

Figure 1. Hierarchy of needs in design

The pyramid shows that poorly designed products will meet only low-level needs whereas a perfect product will fulfill the needs at all levels. Also, it indicates that the design should build on the lower levels first to achieve higher quality. In other words, a product that has good proficiency without providing basic functions cannot satisfy users.

Once the needs for functionality and reliability are fulfilled by clarifying the technology issues, the needs associated with usability are the next hurdle to make the product higher quality. Usability have slightly different definitions and the standards depending on the target product and organization (Abran et al., 2003). However, many standards include three common factors: effectiveness, efficiency and satisfaction. ISO 9241-11 describes the term as the extent that a product provides the three factors to specified users in a specified context of use (ISO, 1998). The definitions of three factors are as shown in Table 2.

Table 2. The Definition of Usability Factors by ISO 9241-11(ISO, 1998)

Factor	Definition
Effectiveness	The accuracy and completeness with which users achieve goals
Efficiency	The resources expended in relation to the accuracy and completeness with which users achieve goals
Satisfaction	The freedom from discomfort and positive attitudes towards the users of the system

Each factor has own measurements. For both effectiveness and efficiency, people focus on the performance of use by measuring percent of errors and time spent, respectively. Many researchers have offered several types of the measurements for evaluating satisfaction level and some examples are following (Hornbæk, 2006): preference, ease of use, perception of outcomes, liking, fun, annoyance, controllability, complexity, intuitiveness, flexibility, attractiveness and physical comfort/discomfort. However, measuring satisfaction is complicated having some weaknesses ranged from a lack of validation to low reliabilities(Chin, Diehl and Norman, 1988). Responses can be biased by experimental circumstances or personal conditions, so the measurements should be resistant to the factors which lead to biased results.

As the definition of satisfaction indicates, comfort or discomfort is critical. According to Story (1998), comfortable use with a minimum of fatigue is indispensable to the products in the universal design. That is, the importance become greater especially when it comes to designing the one-size products that should be usable to anyone regardless physical ability.

2.1.2 Comfort and discomfort - Definition and dimensions

Despite the frequent use of the term, comfort has not been defined homogenously. Three definitions of comfort are described at Table. 3.

At this point, comfort and discomfort is not clearly distinguished. In order to evaluate comfort and/or discomfort, two different

perspectives on comfort and discomfort are utilized regarding the dimension of a scale.

Table 3. Definitions of Comfort

Reference	Definition of Comfort
Merriam-Webster (2005)	"A state or situation in which you are relaxed and do not have any physically unpleasant feelings caused by pain, heat, cold, etc."
Slater (1985)	"A pleasant state of physiological, psychological and physical harmony between a human being and its environment"
Richards (1980)	"A state of a person involving a sense of subjective well-being, in reaction to an environment or situation"

The first perspective is that comfort and discomfort are two independent entities which can be complementary to each other. That is, not being comfort does not mean discomfort. From this point of view, comfort is associated with emotional well-being and relaxation, so factors that enhance comfort are regarded as more advanced requirements. On the other hand, discomfort is related to physical or biomechanical factor, so preventing discomfort is regarded as basic or minimum requirement.

Many studies focused on either comfort or discomfort. For instance, Freund, Takala and Toivonen (2000) and Witana et al. (2009)

focused on comfort in using screwdriver and footwear, respectively. Also, the study related to floor heating utilized the comfort scale. Meanwhile, Shin and Zhu (2011), Liao and Drury (2000), Camilleri (2013) concentrated on discomfort related to visual display terminal (VDT). Fellows and Freivalds (1991), Drury et al. (2006), Wang and Trasbot (2011) and Crane et al. (2005) focused on discomfort resulting from the use of various objects: hand tool, working posture, in-vehicle reach, and wheelchair, respectively. This perspective has been applied to, in particular, the case of designing seats. (Kyung, Nussbaum and Babski-Reeves, 2008; Zhang, Helander and Drury, 1996).

Some studies used both scales for evaluating computer mouse devices and finding postural effects on laptop (Asundi et al., 2010; De Korte et al., 2008).

The second perspective is that comfort and discomfort are two opposite extremes on a single continuum. That is, ‘not being comfort at all’ is same as discomfort. The studies ranged from seat to helmet have been done by using the continuum scale (Abeysekera and Shahnavaz, 1988; Parsons and Griffin, 1982; Shackel, Chidsey and Shipley, 1969). The studies that used the concept of the bi-dimensional comfort scale are relatively small in number comparing the studies which utilized the independent scales. Nevertheless, the conclusion of the recent studies done by Kong et al. (2012) and Kuijt-Evers et al. (2004) supported that comfort-discomfort is an identical concept for hand tool. The results advocate that the continuum scale of comfort is suitable for hand tool evaluation.

2.1.3 Measurement of comfort and discomfort

It is controversial that whether subjective criteria are more appropriate than objective criteria in measuring comfort for a body or vice versa. Pressure level and physiological signals such as EEG and EMG are mostly utilized as objective measures. The subjective measurement is normally done as a form of questioners, Likert, Borg's rating or semantic differential scale.

Some studies have applied both measures to assess hand tools (Fellows and Freivalds, 1991; Shin and Zhu, 2011), indoor environments (Corgnati, Ansaldi and Filippi, 2009; Fransson, Västfjäll and Skoog, 2007; Zannin and Marcon, 2007) and car seats (Zschocke and Albers, 2008). On the other hand, Strasser, Wang and Hoffmann (1996), Kong and Freivalds (2003) and Kluth, Kellermann and Strasser (2004) evaluated comfort/discomfort objectively by analyzing EMG data, the others relied on subjective measures (Miller et al., 2000; Nelson, Treaster and Marras, 2000; Park et al., 1998; Swanson et al., 1997). The side supporting the subjective measure for comfort insists that (1) comfort is a construct of a subjectively defined personal nature, (2) comfort is affected by factors of physical, physiological and psychological nature and (3) comfort is a reaction to the environment (De Looze, Kuijt-Evers and Van Dieën, 2003). However, in many cases, the results of subjective and objective measurements were not identical. For example, the research done by Kuijt-Evers et al. (2007) showed an inconsistency between EMG and subjective comfort level in using hand saw.

There is no rule of thumb in measuring comfort because it depends on the research object and other conditions as well as the goal of research. For this study, comfort was measured in both subjective and objective manners by rating 100 points scale and collecting EMG data, respectively.

2.1.4 Comfort and ergonimics

Comfort and discomfort are affected by two ergonomic factors, anthropometric and physiological factors (Kolich, 2003). Physiological factors deal with, for example, ligaments, joints and muscles. Among others, muscle activity has been widely used with its convenience of measure. Muscle activity has been normally quantified by measuring and analyzing electromyography. Two estimators, root mean square (RMS) amplitude, normalized EMG (NEMG) and integral EMG (IEMG) are used here. Larger values of RMS, NEMG or IEMG are directly linked to greater muscle activities(Gerard et al., 1999). For instance, when a person does a performance which requires more force, the related muscles will activate more. EMG signals will fluctuate more widely leading to greater RMS values. The same result can be acquired if the muscle gets fatigue. When consistent amount of force is generated, EMG signals are getting more fluctuated with the occurrence of muscle fatigue. Muscle fatigue can be defined as “any reduction in the ability to exert force in response to voluntary effort” (Bigland-Ritchie et al., 1994; Edwards, 1981) and occurs on a single muscle, locally. EMG signals can be used to investigate local muscle fatigue as well as the magnitude of muscle activity(Vøllestad, 1997). For this reason, it is important to avoid getting fatigue if a researcher

wants to utilize the quantified muscle activity such as RMS for comparing the amount of muscle efforts.

For a dynamic task, it is hard to check whether muscle fatigue occurs or not with RMS or IEMG value because exerted force is not stable, it can be figured out by means of monitoring a shift of power spectrum. If the shape of power spectrum of a certain muscle sheers to the left comparing the initial power spectrum, this means it utilized more at lower frequency and, therefore, muscle fatigue occurs on the specific muscle. The mean spectral frequency (MSF) and median frequency (MEF) can be used as a single estimate to indicate shifts the myoelectric power spectrum (Hägg, Luttmann and Jäger, 2000). This method may help to ensure the existence or the absence of muscle fatigue in dynamic situations.

The other ergonomics criteria is related to anthropometry which is the science dealing with body measurement, such as size, shape, strength, mobility, and flexibility, connecting to working capacity (Pheasant and Haslegrave, 2006). Anthropometry has been a key aspect in design for finding the boundary values of maximum range in which users can utilize or be accommodated with the product without discomfort. Since products are designed for various types of consumers, an important design requirement is to select and use the most appropriate anthropometric database in design (Wickens, Gordon and Liu, 2004). Common applications of anthropometry in design are workspace, sitting, visual display terminal, computer, input devices, handles and handheld devices of which shape, configuration,

arrangement and size should be considered as well as statistical distribution of anthropometric data for user population.

Why is comfort or discomfort state important in ergonomic point of view? If discomfort feeling keeps for a long time, this will lead to impairment of efficiency and musculoskeletal disorders, both caused by muscle fatigue(Hollands and Wickens, 1999; Kuijt-Evers et al., 2004). Musculoskeletal disorders are injuries or malfunctions affecting muscles, bones, tendons, ligaments, cartilages, joints, nerves, and spinal discs.

In occupational field, this issue has been discussed because work-related musculoskeletal disorders (WMSD) are prevalent and costly. This implies that companies can reduce compensation cost by minimizing the disorders of employers. As the National Institute for Occupational Safety and Health (NIOSH) reported, several epidemiological studies have demonstrated that physical exertion at work and WMSD has a causal relationship (Putz-Anderson et al., 1997). The factors associated with WMSD are repetitive motion, excessive force, awkward and/or sustained postures, prolonged sitting and standing (Da Costa and Vieira, 2010). Repetitive motion, in particular, can cause muscle fatigue and musculoskeletal disorders even with small force exerting as low as 5% of Maximum Voluntary Contraction (MVC) (Jørgensen et al., 1988).

Other researches related to comfort in occupational environment have been focused on the degrees of discomfort/pain during work

considering the body posture, work duration and instruments or machines. In these cases, clarifying the relationship between comfort and performance, which were effectiveness and efficiency, was main concern. Nonetheless, user satisfaction is important as much as performance for everyday products outside of workspaces.

2.2 Hand

The human hands are well-designed organ having an infinite variety of function and arrangement so that they can do sophisticated works. With this reason, hands are still used as the primary means for operators even in the occupational environment where all the automation efforts were made. The magnitude of hand health problems is more stressed as computer works using a keyboard, a mouse or other handheld controller become dominant in work places and electronic devices become small enough to be held by hands or even one side.

2.2.1 Anthropometry of the hand

The human hand is defined as the distal end of upper limb ranged from the wrist joint to the finger and has great complexity in its construction. Generally, hand has five fingers with twenty-seven bones. The bones are divided into three groups, eight carpal bones, five metacarpal bones, and fourteen phalanges of the fingers, so the hand can have huge degrees of freedom leading to manual dexterity (Yun, 1994).

Besides skeleton, there is much more complicated muscle system acting on hand, divided into two groups; extrinsic and intrinsic muscles. The extrinsic muscles are located in the anterior and posterior compartments of the forearm. The muscles are grouped into long flexors and extensors and produce crude movements and a forceful grip. Abductor Pollicis Longus (APL), Flexor Digitorum Profundus (FDP), and Flexor Pollicis Longus (FPL) are the exmples of extrinsic muscles, which are activated by finger movements. On the other hand, the intrinsic muscles of the hand are located within the hand itself having responsibility for the fine motor functions of the hand. The intrinsic muscles include Oppenens Pollicis (OP), Abductor Pollicis Brevis (APB), Abductor Digiti Minimi (ADM), Dorsal Interossei and Palmaris Brevis, etc.

With the complex muscular skeletal system, the hands are devoted to functions of complex manipulation handling muscle force. Thus, in regard of hand, functional anthropometry is important as much as static anthropometry. The result of measuring hand dimensions during reaching, pushing, grasping, releasing and rotating motions can be functional anthropometric data. Functional anthropometric data has been also applied for the population with a disability as well as normal people. For the users with arthritis, normal manual operation including rotating, twisting, or pressing may be difficult due to the limit of exerting force and finger movement. According to Fraser et al. (1999), there were no significant difference in static anthropometric hand dimensions between individuals with and without arthritis, but functional data. The results re-emphasized the importance of analyzing

functional anthropometry of hand independently.

National surveys have been done on hand anthropometry in many countries. Gathering anthropometric data of British population from various sources, for example, Pheasant and Haslegrave (2006) provides 20 hand dimensions and the estimates for both male and female population as well as range of movement. Other researches were done targeting US Army (Greiner, 1991), Indian female (Nag, Nag and Desai, 2003) and Vietnamese-American population (Imrhan, Nguyen and Nguyen, 1993). The participants of the studies were limited to biased group, gender, or in number. In Korea, an institution, called Size Korea, also has carried out the human dimensions research and offers the result representing whole population in Korea. However, in most cases, information on functional anthropometric data is insufficient to generally apply due to strong dependency of the context and high degrees of freedom, the surveys are often customized and done in smaller scale.

2.2.2 Hand and comfort

Hand tools are still the primary interface to operate at home and at work even in the environment where all the automation efforts were made. Therefore, comfort is one essential requirement in designing hand tools same as other products. On the purpose of avoiding discomfort, many studies on hand tools have been researched and the type of hand tool that have been studied is dynamic; garden tools((Fellows and Freivalds, 1991), screwdriver and pliers((Kuijt-Evers et al., 2004), hand saw(Kuijt-Evers et al., 2007),

keyboards(Gerard et al., 2002; Rempel et al., 1997), mouse(Lee et al., 2007), mobile phone(Gustafsson, Johnson and Hagberg, 2010), and smart phone(Otten, Karn and Parsons, 2013) were the targets of the studies.

Also, many researchers reported that comfort and discomfort in using hand tools are affected by elements of handle such as length (Mirka, Jin and Hoyle, 2009), angle (Schoenmarklin and Marras, 1989), size (Cochran and Riley, 1986), shape (Kong et al., 2008; Kong et al., 2007; Shih and Wang, 1996), material (Chang, Park and Freivalds, 1999), and weight (Björing and Hägg, 2000).

In addition to traditional approach dealing with hand comfort, a new assessment method, called Hand Activity Level (HAL), has been developed by American Conference of Government Industrial Hygienists (ACGIH). Given Threshold Limit Values and Action Limit for HAL, the method can be used as a tool when evaluating risks of disorders at hand and wrist area. The system has an advantage to determine skeletal muscular risk level easily because it consists of only two variables, hand activity level and normalized peak force. It was applied to some studies testing discomfort in repetitive hand activities, for example, assembly work (Wurzelbacher et al., 2010). The system is, however, at start-up stage, thus, not fully verified yet (Kim et al., 2006). However, the fact that the new method has been being developed holds up a true mirror to the importance of preventing the disorders related to hands.

Some risk factors inducing wrist/hand WMSD, for example, Carpal tunnel syndrome, over used hand syndrome and De Quervains' disease, have been discovered. According to Da Costa and Vieira (2010), main risk factors for wrist/hand WMSD is caused by computer work, heavy physical work, and repetitive work even exerting low level force. This implies if a user repetitively operates a hand device for a long time, wrist/hand WMSD can occur not only at work, but also in daily life. However, researches have rarely been done on daily-used hand tools such as mobile phone including touchscreen smart phone.

2.3 Researches Done on Smartphone

Smartphone is a kind of everyday product used most. Mostly, the smartphone is equipped with touchscreen having many advantages. The touchscreen smartphone are operated by invisible and embedded interaction which requires natural human skill (Fishkin, Moran and Harrison, 1999), and quick use and instant on/off functions are adorable (Tambe, 2012). Also, tasks of touchscreen devices are simple (Kwon, Choi and Chung, 2011); tapping including typing, dragging including radial movement without any input device except the fingers.

Many related studies for the touchscreen smartphone have been done mostly on usability (Han et al., 2001; Jin and Ji, 2010; Park et al., 2011; Perry and Hourcade, 2008) and a few have been done on physiological factor of comfort using EMG data. Most researches

associated with user interface are limited to size of target, thumb envelope area or the location of target from efficiency and effectiveness perspectives(Jin, Plocher and Kiff, 2007; Otten, Karn and Parsons, 2013; Perry and Hourcade, 2008).

According to a study on the postures when using mobile devices done by Gold et al. (2012), $\frac{1}{3}$ of population use the device with a single hand. The exsiting studies related to one-handed thumb use focused on the target size effect or technological issues (Karlson and Bederson, 2007; Parhi, Karlson and Bederson, 2006).

2.4 Limits of Previous Studies

Many researches have been conducted on hand tools, but the main concern was to avoid impairment of efficiency and musculoskeletal disorders in occupational field; the researches on comfort in using hand tools in daily life such as touchscreen smartphone have not been completed.

Moreover, the relationship between hand anthropometry and smartphone use has not been investigated. Most studies have focused on the device, but not considered the variability of the users much, even though the device is the representative one-size product. Also, it is not clear whether hand size or shape affect comfort of performing basic tasks of touchscreen, such as tapping and dragging. Detailed guides on

interfaces associated with thumb activities are not sufficient, either.

Most studies on touchscreens have been weighted on objective comfort, too. Curved handheld touchscreens which have been released to the market have not been investigated regarding both kinds of comfort.

Lastly, studies to analyze the one-hand usage have rarely done. The existing studies are not connected with anthropometric factors of comfort nor connected to muscle activities when using with one hand.

Chapter 3. Research Methodology

3.1 Hypothesis

This study only considered the case of the users handling the device with a single preferred hand without occurring muscle fatigue.

Since the curved devices have just been released, the effect of curvature on comfort has not been discovered yet. Accordingly, this study postulates that:

Hypothesis 1 (H_1): Curvature of the devices affects subjective and objective comfort when using the handheld touchscreen devices with one hand.

Based on the research of previous studies, it was insufficient to clarify the relation between the hand anthropometry and comfort when using the touchscreen smartphone, although it is the one-size product. The first null hypothesis, H_2, was postulated to be tested.

Hypothesis 2 (H_2): The size and shape of hand affect subjective and objective comfort when using the handheld touchscreen devices with one hand..

Also, in order to investigate the detailed physical interactions of the thumb, the following hypothesis was proposed:

Hypothesis 3 (H_3): Objective comfort varies with the level of dragging and tapping tasks when using the handheld touchscreen devices with one hand

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3.2 Statistical Analysis on Hand

The human hand has various anthropometric dimensions as well as other body parts. For the experiment, 18 static anthropometric dimensions of hand related to touchscreen use were selected. (Table 4)

Table 4. 18 static anthropometric dimensions related to touchscreen smartphone use

Hand dimension
Hand Circumference
Hand Breadth
Hand Depth
Hand Length
Inner Grip Circumference
Radial styloid-thumb fingertip length
Maximum finger span breadth
Palm length perpendicular
Finger length (Thumb/ Index finger/ Medius finger / Ring finger / Little finger)
Capitate – Finger First crease line length (Thumb/ Index finger/ Medius finger / Ring finger / Little finger)

The anthropometric data were provided by Size Korea, and participants were 156 females and 186 males, aged from 20 to 80. In order to figure out the effect of anthropometric factors on touchscreen usage, two step cluster analysis has been executed. The groups classified by hand size using the value of actual hand dimension will be attained though this analysis. Moreover, the other classification of group by hand shape will be achieved with normalized dimensions by hand length. Prior to do clustering, the number of dimensions reduced through factor analysis.

3.3 Apparatus

Three mock-up of touchscreen were prepared. Reference model for size was Samsung's Galaxy Note of which width and depth were 73mm and 8.3mm, respectively. Also, one of the devices had a flat surface same as conventional touchscreen smartphones, and the other had curvature 400R referring to the existing curved device, called Galaxy Round. Curvature 400R denotes the surface is curved as much as the arc of a circle of radius 400cm is curved. The last one had more extreme curvature, 100R. The size details of the mock-ups are described at Figure 2, 3 and 4.

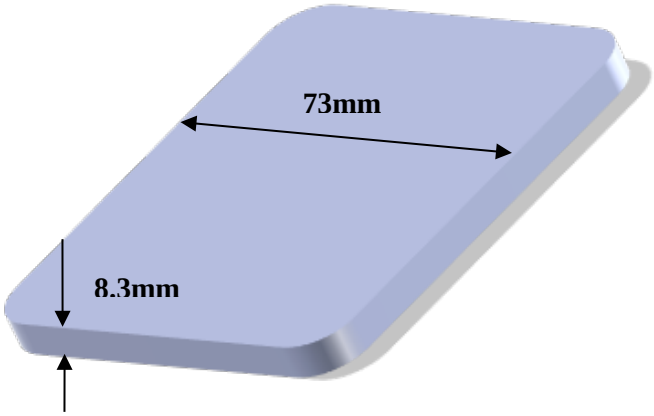

Figure 2. A touchscreen smartphone mock-up, flat

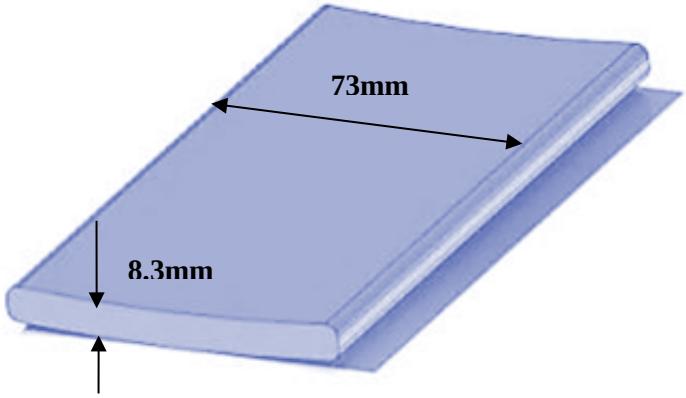

Figure 3. A touchscreen smartphone mock-up with the curvature, 400R

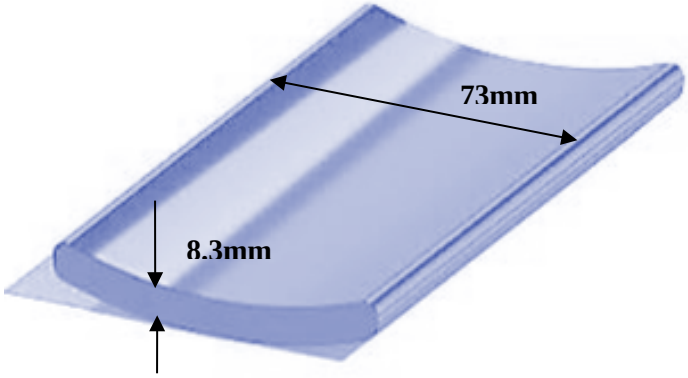

Figure 4. A touchscreen smartphone mock-up with the curvature, 100R

3.4 Subjects

Fifteen college students aged from 20 to 25 were participated in the experiment. The participants were 14 male and one female and all right-handed. Discriminant analysis will be performed to determine the group which a person belongs to later. Descriptive statistics of anthropometric data of the participants 18 will be presented on Appendix D.

3.5 Experimental Design

3.5.1 Tasks

The most comfortable thumb enveloping range of handheld devices has been investigated (Otten, Karn and Parsons, 2013). It is the area that people fill in when swiping thumbs across the screen as illustrated in Figure 5. All tasks of tapping, typing and dragging were assigned within common thumb enveloping range centering at lower right corner. Also, all tasks were performed by using the participant's preferred hand and one-handed thumb interaction could be observed.

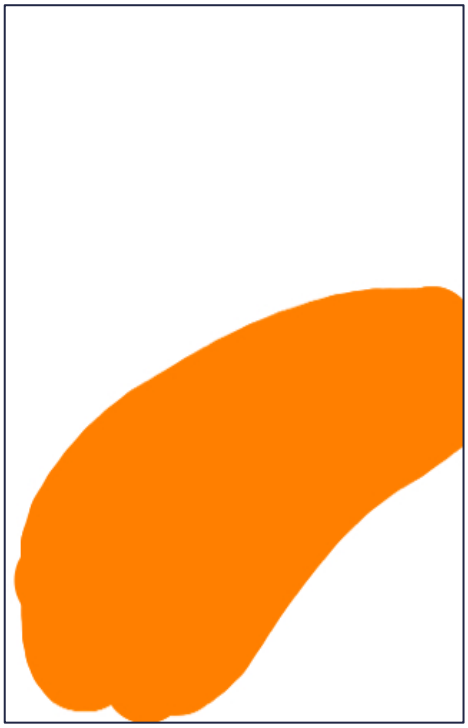

Figure 5. An example of thumb reach envelope colored with orange on a touchscreen smartphone

For the tapping tasks, the participants were asked to select targets at five different positions as shown in Figure 6. The targets were located by equal spaces within the thumb envelope area, and it was assumed that five was the most reasonable deciding the number of targets considering size of thumb. No such action as re-grasping was allowed for this task.

Dragging tasks included eight different directions (N, NE, E, SE, S, SW, W, and NW). Usability test result from previous study varied by dragging direction (Cockburn, Ahlström and Gutwin, 2012), so it was reasonable to fine the effect of direction on the muscle activities in the dragging task. The participants were induced to drag along the given

lines as shown in Figure 7. All lines had identical length, 25mm.

For the typing tasks, three Korean words were given: ‘싫어’, ‘미안’ and ‘사랑’. The reason for including typing task in the scope of this study was that repetition is important factor regarding comfort because repetitive tasks had high risk to occur body fatigue. For the population who keep holding smart phone and text messaging all the time, it was likely getting high risk of hand muscle fatigue. In this experiment, the letters used most frequently such as ‘ㅇ’, ‘ㄴ’, ‘ㅅ’ and ‘ㅏ’(Jeong, 2013) were selected. The keyboard of the experimental device referred to the one of Galaxy Note (Samsung) with the size and style.

Figure 6. Display for tapping task

Figure 7. Display for dragging task

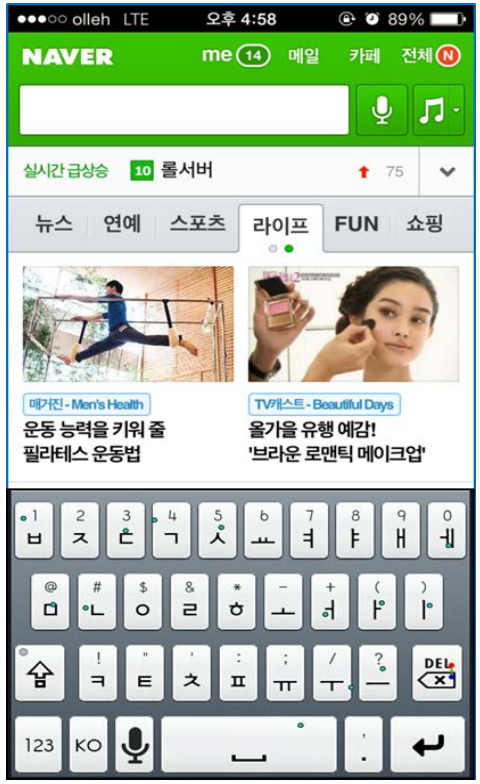

Figure 8. Display for typing task

3.5.2 Measurements

Mainly, there were three measurements, subjective and objective comfort level as well as hand anthropometry. Eighteen anthropometric dimensions in Table 4 were recorded at the beginning of the experiment and used for discriminant analysis to determine pertinent hand group. The results of cluster analysis on the hand data representing Korean population on section 3.1 were applied here.

In order to measure the objective comfort level, EMG signal were recorded. The electrodes were attached to four muscles putting in hand motion: Abductor Digiti Minimi (ADM), Opponens Pollicis (OP), Flexor Digitorum Profundus (FDP) and Flexor Pollicis Longus (FPL). ADM is a muscle of hand activated by abduction of little finger. This muscle works as a support at the bottom of the device when holding it with one hand. OP is other hand muscle that is activated by opposition of the thumb to the little finger. Reaching a certain positions on touchscreen requires activating this muscle cupping the palm and accommodating the thumb to varying location(Marzke et al., 1998). Last two muscles are located on forearm. FDP is related to gripping on thin and relatively wide device such as handheld touchscreens, by flexing distal phalanges of digits 2 through 5 (Berguer et al., 1999). In order to flex distal phalanx of the thumb, FPL is activated, so this can be utilized when thumb selects or precisely acquires a target (Hamrick et al., 1998).

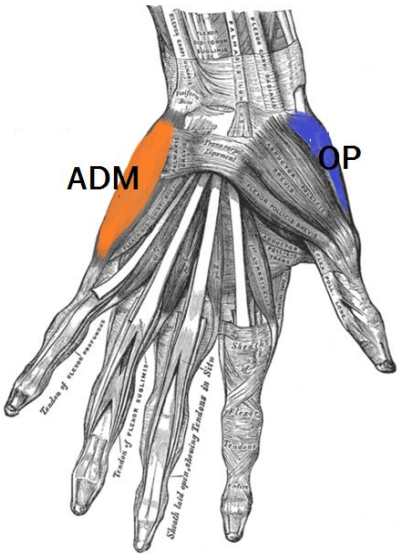

Figure 9. Muscles located on a hand: Abductor Digiti Minimi (ADM) and Opponens Pollicis (OP)

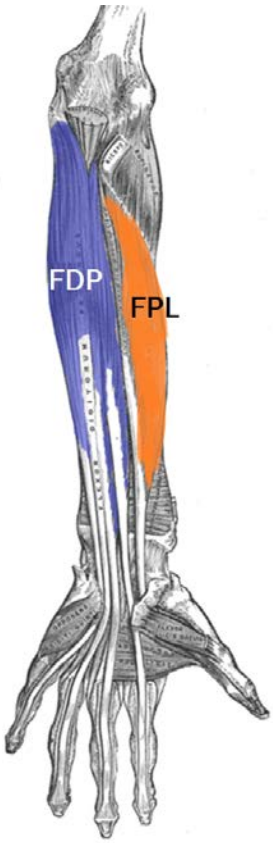

Figure 10. Muscles located on a forearm: Flexor Digitorum Profundus (FDP) and Flexor Pollicis Longus (FPL)

Figure 11. ADM activation by abduction of a little finger (left), a little finger supporting the device (right)

Figure 12. OP activation by opposition of a thumb to the little finger (left), a thumb reaching on the screen (right)

Figure 13. FDP activation by flexing distal phalanges of digits 2 through 5 (left), fingers gripping the device (right)

Figure 14. FPL activation by flexing distal phalanx of a thumb (left), a thumb precisely selecting a target

The EMG signals were monitored in real time to control the quality and simultaneously recorded on-line at 1024Hz by using Laxtha's WEMG 5308 system and a software, Telescan™. The EMG signal recorder was wireless, so unnecessary noise could be avoided. The raw EMG signal was band-pass filtered between 13 - 430 Hz. Two EMG parameters were extracted from the raw EMG signal. The RMS value of rectified EMG was calculated to quantify the muscle activity. In addition to RMS, MEF was calculated using a Fast Fourier Transformation (FFT) to check muscle fatigue occurrence.

Figure 15. Laxtha's WEMG 5308 system

Subjective comfort was evaluated right after one set of experiment doing the three tasks with one sample had been completed. The participants rated the level of comfort using 100-points continuum scale meaning that 0 and 100 equaled extremely discomfort and extremely comfort, respectively.

3.5.3 Procedure

The experiment took 45 to 50 minutes including two break times. A simple explanation of the process was given to each participant at the beginning of the experiment and 18 dimensions of preferred hand of the participant were measured by a vernier caliper (micrometer), a truncated-cone-shape measuring device and a tapeline.

Then, a ground or reference electrode was attached on an elbow joint. The ground electrode needs to be placed at a location in which the risk for a large common mode disturbance signal will be minimal. It is generally accepted that reference electrodes need to be placed on electrical inactive tissue such as the elbow joint (Hermens et al., 2000). Through simple muscle activation, the locations of four muscles (ADM, OP, FDP, FPL) were found and the electrodes were attached on the most appropriate points not to disturb use of the device.

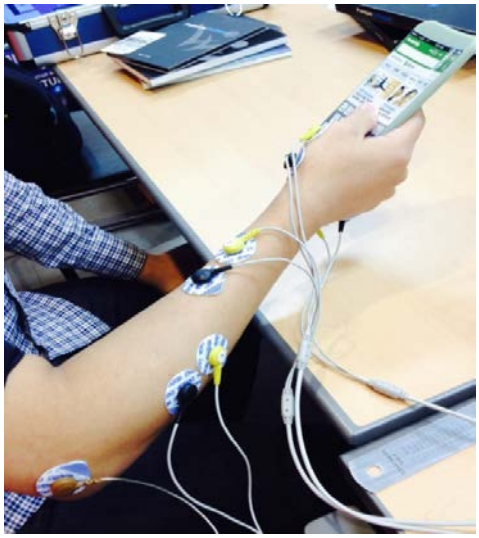

Figure 16. Four pairs of electrodes and a reference electrode attached on the hand and forearm

Before performing tasks, maximum voluntary contraction (MVC) values of each muscle were recorded individually. Standardized methods of exerting MVC of each muscle were applied for all participants. Each muscle contracted three times and the greatest value among the three trials was recorded as MVC. The value of MVC was used as a reference value for normalizing muscle activities for each muscle.

Three tasks were performed in the order of tapping, typing and dragging with a given hand posture as illustrated in Figure 17. All activities of each muscle were recorded while the participant coped with all tasks.

In order to check the local muscle fatigue during the experiment, MVC for each muscle were measured again.

Figure 17. Given hand posture; holding device in one hand with little finger support

Once one experiment corresponding one sample was done, the participant took a rest at least 5 minutes to keep the same experimental condition without muscle fatigue, since this experiment focused on the muscle activities of three devices. During the break, subjective comfort for the device was evaluated. After the break, the three tasks were repeated having other two devices. The orders of the device given to the participants were randomly chosen to eliminate order effects.

3.6 Data Analysis

SPSS (PASW 18 , SPSS Inc.) was used to perform statistical analysis such as analyses of variance (ANOVA) followed by Scheffe's post hoc Test at a significance level of 0.05, simple linear regression analysis, and discriminant analysis. For the classification of the descriptors into factors, principal compound analysis (PCA) with verimex rotation was applied.

Telescan™ (version 3.06, Laxtha) was utilized to analyze the raw EMG signals. RMS operations, RMS calculation and power frequency spectrum analysis including MEF method with bandwidth 20Hz to 450 Hz were performed.

Chapter 4. Results

4.1 Group classification by the size and the shape of hand

Initially, 18 dimensions of the hand related to the unimanual use of handheld device were drawn. Given the relevant data of Korean population, the number of dimensions was reduced to by factor analyzing. Operating the factors, the hands of Korean population were clustered according to size and shape.

4.1.1 Group classification by actual size of hand

The value of Keiser-Meyer-Olkin (KMO) sampling adequacy and Bartlett's test of sphericity were 0.942 and 0.000, respectively. Therefore, factor analysis could be done with the data. By factor analysis, the number of dimensions decreased to four. Only if the factor loading of a dimension was less than 0.6, it was regarded as a separate factor, so that the maximum finger span breadth with loading value of 0.581 became an independent factor. The result is presented in Table 5.

According to the result of clustering having the four factors above, there are three significantly different groups in Korea with fair cluster quality if hand size is concerned. The first group has characters of longer finger length, higher volumes, longer finger span breath and bigger palm. The second group has the other way around; shorter finger and span breath as well as smaller volume and palm. The last group is

on the mid-point of them. The proportions of the groups among the data set are following. (See Table 6.)

Table 5. The result of factor analysis on the actual hand size

Factor	Dimension	Component		
		1	2	3
Palm	Capitate-Finger First Crease Line Length, Medius Finger	**.888**	.310	.267
	Capitate-Finger First Crease Line Length, Ring Finger	**.879**	.321	.226
	Capitate-Finger First Crease Line Length, Little Finger	**.863**	.304	.224
	Capitate-Finger First Crease Line Length, Index Finger	**.850**	.335	.294
	Capitate-Finger First Crease Line Length, Thumb	**.823**	.205	.275
	Palm Length Perpendicular	**.753**	.409	.325
	Radial Styloid-Thumb Fingertip Length	**.631**	.392	.238
Hand length	Finger Length, Index Finger	.278	**.858**	.274
	Finger Length, Medius Finger	.323	**.838**	.285
	Finger Length, Ring Finger	.325	**.828**	.307
	Finger Length, Little Finger	.266	**.774**	.294
	Finger Length, Thumb	.261	**.708**	.415
	Inner Grip Circumference	.340	**.676**	-.179
	Hand Length	.639	**.647**	.314
Maximum Finger Span Breadth		.364	***.581***	.454
Hand Volume	Hand Depth	.271	.138	**.828**
	Hand Circumference	.333	.351	**.807**
	Hand Breath	.427	.347	**.731**

Table 6. Distribution of the groups classified by the actual hand size

Group	Description	Proportion of population	Number of corresponding participants
A1	Big-size hand	30.6 %	2
A2	Mid-size hand	36.4%	6
A3	Small-size hand	33.0%	7

4.1.2 Group classification by shape of hand

In order to consider the shape of hand, all values of data set were normalized by hand length for each participant. That is, the dimensions changed to the ratio of hand length. Same as the previous case, the pre-test for factor analysis for the new data set was completed. The new data set was suitable for factor analysis with the value of 0.907 for KMO sampling adequacy and 0.000 for Bartlett's test of sphericity. At this time, the number of dimensions decreased to six having the same logic with grouping by size previously done. Table 7 shows the result.

The six factors were utilized for clustering. Through this analysis, four groups which have significant difference of hand shape are emerged for Korean population. The first group has the smallest proportion of palm, but the widest range of thumb reach relative to absolute hand length. The second group has the greatest portion of palm and radial styloid-thumb fingertip length. The characters of the third group are smaller ratio of thumb and radial styloid-thumb fingertip length. The last group is rare, but has bigger portion of radial styloid-thumb fingertip line and much smaller volume and the range of thumb reach. Refer to Table 8 to see the size of groups.

Table 7. The result of factor analysis on normalized hand size

Factor	Dimension	Component				
		1	2	3	4	5
Palm	Capitate-Finger First Crease Line Length, Ring Finger	**.904**	-.183	.005	.078	-.025
	Capitate-Finger First Crease Line Length, Little Finger	**.877**	-.120	-.004	.012	-.124
	Capitate-Finger First Crease Line Length, Medius Finger	**.876**	-.292	.082	.007	.132
	Capitate-Finger First Crease Line Length, Index Finger	**.807**	-.182	.142	-.052	.220
	Capitate-Finger First Crease Line Length, Thumb	**.711**	-.043	.143	-.200	.272
Finger length	Finger Length, Medius Finger	-.213	**.843**	.003	.004	.091
	Finger Length, Ring Finger	-.151	**.839**	.070	.050	.169
	Finger Length, Index Finger	-.176	**.786**	.032	.210	.163
	Finger Length, Little Finger	-.019	**.717**	.079	.145	-.180
	Palm Length Perpendicular	.331	**-.632**	.199	.203	.224
Hand thickness	Hand Circumference	0.015	.067	**.901**	-.033	.115
	Hand Breath	0.111	.018	**.847**	-.069	.015
	Hand Depth	.108	-.041	**.779**	.030	.037
Thumb reach	Inner Grip Circumference	-.054	.039	-.349	**.730**	.047
	Maximum Finger Span Breadth	.076	.193	.442	**.602**	-.327
Finger Length, Thumb		-.151	.330	.331	***.509***	.425
Radial Styloid-Thumb Fingertip Length		.321	.065	.079	-.019	**.782**

Table 8. Distribution of the groups classified by the hand shape

Group	Description	Proportion of population	Number of corresponding participants
S1	Small palm ratio	36.5 %	10
S2	Big portion of radial styloid-thumb fingertip and palm	35.6%	2
S3	Short thumb	25.7%	3
S4	Skinny hand and narrow range of thumb reach	2.2%	1

4.2 General statistical results of muscle activity and comfort

The measured EMG data and subjective comfort level were analyzed using descriptive statistics, mean and standard deviation. According to the result, all three devices required to consume 8.858% of MVC, on average. In other words, users utilize the four hand muscles as much as 8.858% of their maximum ability. Instantaneously, it was sometimes observed that the value increased up to 70% of MVC. Also, the participants felt the mock-up with 400R curvature most comfortable. The flat mock-up achieved lowest comfort score with the greatest variation; someone likes the flat device, but the other one dislike it.

Table 10 represents the result of same analysis on each task. The tapping and dragging task averagely activated muscles approximately 8 to 9% of MVC and the dragging task had more consistent use of

muscles. When typing, the muscles were used 2% more, that is 10% of MVC.

Table 9. Descriptive statistics on muscle activity and subjective comfort level for the three mock-ups

Curvature	Statistics	Muscle usage (%MVC)	Comfort level
Flat	Mean	8.956	66.333
	Standard Deviation	7.720	15.004
400R	Mean	8.755	76.333
	Standard Deviation	7.561	12.717
100R	Mean	8.864	69.667
	Standard Deviation	7.336	11.620
Total	Mean	8.858	70.778
	Standard Deviation	7.538	13.825

Table 10. Descriptive statistics on muscle activity for three tasks; tapping, dragging and typing

Task	Statistics	Muscle usage (%MVC)
Tapping	Mean	8.352
	Standard Deviation	8.510
Dragging	Mean	8.526
	Standard Deviation	6.573
Typing	Mean	10.589
	Standard Deviation	7.979
Total	Mean	8.858
	Standard Deviation	7.538

When looking at the muscle individually, differences were observed in mean values. Muscle activities of OP, activated by moving

thumb toward little finger, were the greatest among muscles having the value of 12.176% of MVC. On the other hand, FDP which was used when gripping the device with the end of four digits except thumb was used least. Supporting the bottom of the device, ADM utilized 6.719% of MVC on average with 5.614% of standard deviation. The average value is small comparing the results of FPL and OP. FPL related to flexing distal phalanx of thumb showed over 11% of MVC consumption, but much uniformly comparing to OP. Table 11 summarized the result.

Table 11. Descriptive statistics of muscle activity for each individual muscle and in totality

Muscle	Statistics	Muscle usage (%MVC)
ADM	Mean	6.719
	Standard Deviation	5.614
OP	Mean	12.176
	Standard Deviation	10.415
FDP	Mean	4.890
	Standard Deviation	3.572
FPL	Mean	11.647
	Standard Deviation	5.970
Total	Mean	8.858
	Standard Deviation	7.538

4.3 The Effects of Curvature on Muscle Activity and Comfort

An analysis of variance (ANOVA) was performed on the independent variable, muscle activity expressed as the percent of MVC

and comfort level, and on the dependent variable, curvature which was the determinant of type of sample ($\alpha = 0.05$). In addition to ANOVA, regression analysis on the inverse values of curvature and comfort level was used for curve fitting.

4.3.1 The effect of curvature on muscle activity

The ANOVA result showed that total muscle activities adding all muscles did not significantly differ in curvature ($p = 0.843$). The results were same when the cases were narrowed down to each muscle. See table 12.

Table 12. Result of analysis of variance on muscle activities between curvatures for each individual muscle

Muscle type	p – value ($\alpha = 0.05$)
ADM	0.835
OP	0.832
FDP	0.345
FPL	0.829

Several ANOVA tests were performed to find the differences in the type of mock-up with the dependent variable, % MVC, by controlling other categorical variables; in this case, muscles, tasks and groups of hand respecting size and shape. Most of cases, muscle activities were not affected by curvature. However, a significant result was found that values of %MVC of FDP; the small-hand size group showed significant difference in curvature when they did the dragging task, in particular ($p < 0.01$). With the same task, the group S2

distinguished by big portion of radial styloid-thumb fingertip and palm showed different muscle activities on FDP in curvature (p< 0.01). Table 13 describes the details.

Table 13. Result of analysis of variance on the activity of FDP between curvatures in dragging for the small hand group

%MVC, Mean (Standard deviation)

	Curvature			F	Scheffe test
	Flat	400R	100R		
Muscle Activity on FDP	3.1199 (.576)	2.4376 (.873)	3.4804 (.550)	9.641**	100R , Flat > 400R

** $p < 0.01$

4.3.2 The effect of curvature on comfort level

Comfort levels were significantly different according to curvature proved by an ANOVA test (p < 0.01). Subsequent to the ANOVA test, Scheffe's post hoc test was used to examine specific variable difference. The result showed that moderately curved device of which curvature was 400R achieved the highest comfort level, whereas flat device evaluated as the least comfortable.

Table 14. Result of analysis of variance on comfort level between curvatures

Comfort level, Mean (Standard deviation)

	Curvature			F	Scheffe test
	Flat	400R	100R		
Comfort level	66.333 (15.00)	76.333 (12.72)	69.667 (11.62)	143.073**	400R > 100R > Flat

** $p < 0.01$

A test for curve fitting which explains the best fit of comfort level as a function of curvature was conducted as well. For the collected data, quadratic equation is the most appropriate model as Equation 1 and the graph is as shown in Figure 18.

$$\text{Comfort level} = 68.571 + 5607.143 \cdot {}^{1}/_{CR} - 528571.427 \cdot {}^{1}/_{CR^2}$$

CR = Curvature (unit: R)

Equation 1. Quadrant equation for curve fitting model of comfort level and curvature

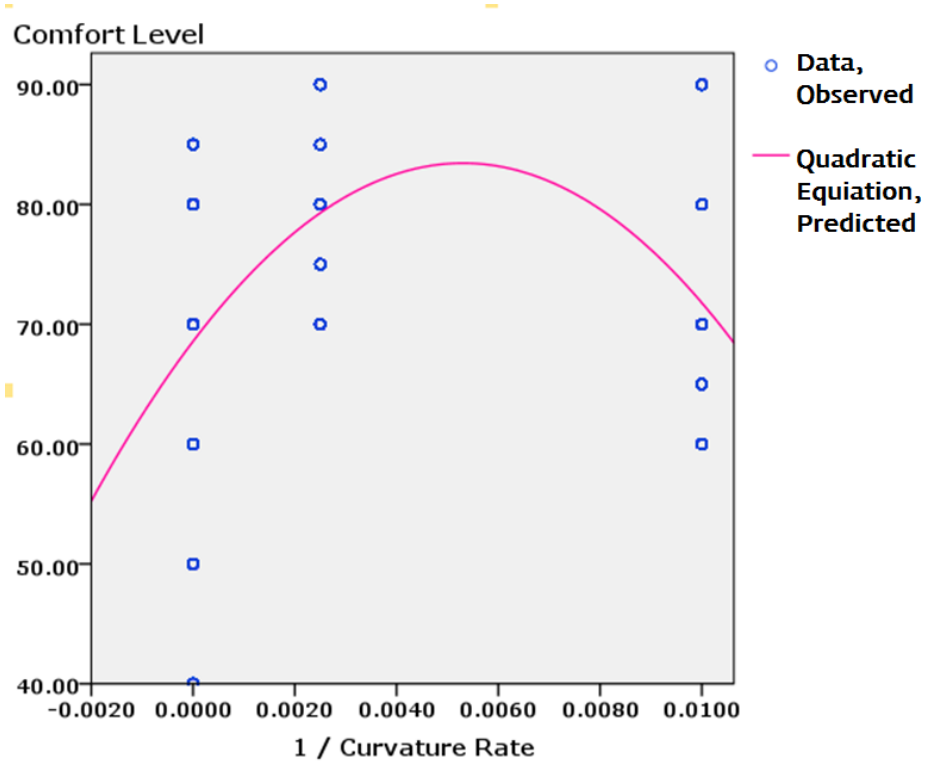

Figure 18. Quadratic curve fitting model for inverse of curvature and comfort level (R^2 = 0.175, $p < 0.01$)

As the graph illustrated, comfort level increases until 1/curvature becomes around 0.006 at which the curvature is around 170R and turns to decrease. This prediction means users are expected to satisfied most with a device of which curvature is in-between 400R and 100R being consist with the participants' comment.

4.4 The Effects of Size of The Hand on Muscle Activity and Comfort

Same as verifying the effect of curvature on the muscle activity and comfort level, ANOVA was performed to find differences of muscle activity (%MVC) and comfort level among the groups classified by size of hands ($\alpha = 0.05$).

4.4.1 The effect of the hand size on muscle activity

The result of ANOVA test shows that the overall activity of muscles when performing with the three mock-ups significantly differs in the actual hand size ($p < 0.01$). According to the result of post hoc test, group 2 and 3 activates muscles less than group 1. This is interpreted as the big-size hand group utilizes muscle less than the groups with smaller hand. Additional ANOVA tests were done for the muscles, individually. For each muscle, the %MVC values were not identical across all groups although the result was distinguished from the magnitude and the order. In most cases, group A1 used muscles least, except FDP. Refer to Table 15 for the details.

Table 15. Result of analysis of variance on the muscle activity between the groups classified by the hand size in totality and for each individual muscle

%MVC, Mean (Standard deviation)

Muscle Activity	Group			F	Scheffe test
	A1	A2	A3		
Overall	7.180 (6.972)	10.486 (7.955)	9.849 (6.908)	66.334**	A1 < A2, A3
ADM	3.706 (1.88)	9.774 (7.07)	8.102 (3.57)	126.871**	A1 < A3 < A2
OP	10.645 (9.95)	13.573 (11.23)	13.343 (8.67)	6.939**	A1 < A2, A3
FDP	4.594 (4.00)	5.682 (3.40)	3.554 (1.15)	15.561**	A3 < A1 < A2
FPL	9.778 (6.22)	12.913 (5.20)	14.400 (5.18)	36.378**	A1 < A2 < A3

** $p < 0.01$

Also, each sample having identical curvature came out same result. Interesting fact is that group 1 of which members had the greatest size of hand dimensions was consistently differentiated from smaller-hand population (group A2 and A 3) as shown in Table 16.

Table 16. Result of analysis of variance on muscle activities between the groups classified by the hand size for each mock-up.

%MVC, Mean (Standard deviation)

Curvature	Group			F	Scheffe test
	A1	A2	A3		
Flat	7.067 (7.22)	10.822 (8.05)	9.974 (6.86)	27.154**	A1 < A2, A3
400R	7.341 (7.17)	9.990 (7.71)	9.999 (7.63)	15.126**	A1 < A2, A3
100R	7.134 (6.52)	10.646 (8.10)	9.573 (6.20)	25.628**	A1 < A2, A3

** $p < 0.01$

4.4.2 The effect of the hand size on comfort

Comfort levels were significantly different among all groups ($p < 0.01$). Subsequent to the ANOVA test, Scheffe's post hoc test was used to examine specific variable difference. The result showed that mid-size hand group scored highest comfort level on average and big hand users did the other way around. Also, the small hand users showed inconsistent responses supported by great variances.

Table 17. Result of analysis of variance on comfort level between the groups classified by the hand size

Comfort level, Mean (Standard deviation)

	Group			F	Scheffe test
	A1	A2	A3		
Comfort level	66.9 (17.22)	75.56 (8.81)	70 (6.46)	133.374**	A1 < A3 < A2

** $p < 0.01$

4.4.3 The compound effect of curvature and the hand size on comfort

To find the interaction effect between the hand size and curvature on comfort level, two factor ANOVA was performed, and the outcome indicated that there was interaction effect ($p < 0.01$, $F = 27.919$). The result is visualized as figure 19. Regarding flat mock-up, three groups rated comfort level differently and group A1award much lower comfort score to the flat device than other groups. For the moderately curved mock-up (400R), group A2 rated especially high score, and the levels rated by group A1 and A3 were almost identical. The ratings were more

converged having most curved mock-up (100R), but the values from the groups were lower than the moderately curved one.

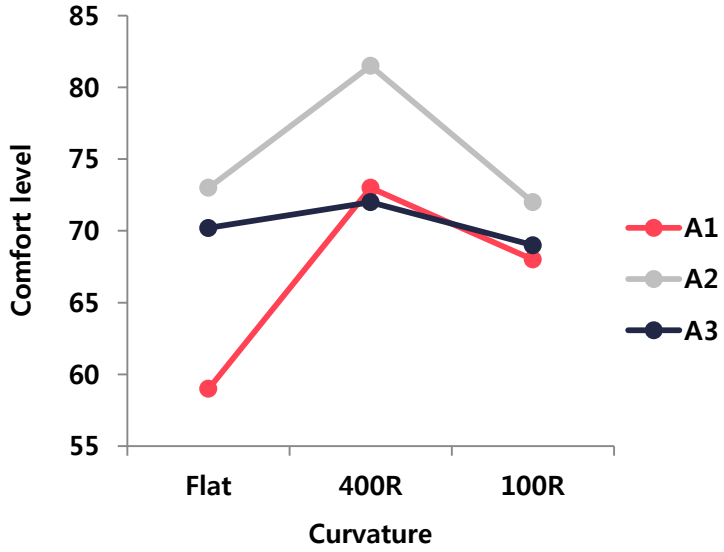

Figure 19. Relationship between curvature and comfort level for each group

4.5 The effect of the hand shape on muscle activity and comfort

In this section, the result of ANOVA test was used to determine whether the difference of muscle activity (%MVC) and subjective comfort level existed by the groups classified by the shape of hands or not ($\alpha = 0.05$).

4.5.1 The effect of the hand shape on muscle activity

The ANOVA result indicates that overall activity of muscles when performing with all devices significantly differs in the hand shape ($p <$

0.01). It was found by post hoc test that group S2 activated muscles most and group S1 did least. Each muscle differed from the %MVC values although they were distinguished from details. Refer to Table 18 for the details. Group S1 and S4 showed stark differences in the activities of all muscles.

Table 18. Result of analysis of variance on muscle activity between the groups classified by the hand shape in totality and for each individual muscle

%MVC, Mean (Standard deviation)

Muscle Activity	Group				F	Scheffe test
	S1	S2	S3	S4		
Overall	8.932 (7.84)	9.489 (8.14)	7.198 (5.71)	11.912 (7.11)	21.204**	S1 < S3, S2 <S4
ADM	5.790 (4.93)	8.461 (6.16)	7.042 (6.89)	10.622 (2.70)	15.835**	S1, S3 < S2 <S4
OP	13.783 (10.54)	13.515 (11.92)	5.372 (0.45)	16.658 (8.06)	34.060**	S4 << S1, S2, S3
FDP	4.121 (2.75)	3.883 (1.46)	8.210 (5.06)	3.872 (1.01)	66.092**	S4, S2, S1< S3
FPL	12.033 (6.15)	12.096 (5.36)	8.573 (4.61)	16.494 (4.45)	26.626**	S3 < S1, S2 <S4

** $p < 0.01$

Overall %MVC values from each group were not all same, either. Similar to groups classified by size, for both of non-flat mock-ups (400R and 100R), group S4 of which members had thin hand and narrow range of thumb movement utilized muscles more consistently than other groups as shown in Table 19.

Table 19. Result of analysis of variance on muscle activity between the groups classified by the hand shapes for each mock-up.

%MVC, Mean (Standard deviation)

Curvature	Group				F	Scheffe test
	S1	S2	S3	S4		
Flat	9.100 (7.81)	10.426 (9.23)	6.587 (5.59)	11.820 (7.26)	10.906**	S3 < S1, S2 <S4
400R	8.854 (8.03)	8.886 (6.96)	7.061 (5.84)	12.677 (7.46)	9.231**	S3, S1, S2 <S4
100R	8.841 (7.69)	9.154 (8.04)	7.945 (5.64)	11.237 (6.61)	3.330*	S3 ,S1, S2 <S4

** $p < 0.01$

* $p < 0.05$

4.5.2 The effect of the hand shape on comfort

The subjective evaluation on comfort level was significantly different among the groups ($p < 0.01$). Subsequent to the ANOVA test, Scheffe's post hoc test was used to examine specific variable difference. Table 20 represents the result. Same as the groups classified by the hand size, the groups by the hand shape did not evaluate comfort homogenously.

Table 20. Result of analysis of variance on comfort level between the groups classified by the hand shapes

Comfort level, Mean (Standard deviation)

	Group				F	Scheffe test
	S1	S2	S3	S4		
Comfort level	68.703 (16.25)	70.000 (5.78)	77.222 (8.54)	71.667 (6.25)	58.681**	S1 ,S2 < S3 <S4

** $p < 0.01$

4.5.3 The compound effect of curvature and the hand shape on comfort

To find the interaction effect between the hand shape and curvature on comfort level, two factor ANOVA was performed, and the outcome indicates that there was an interaction effect ($p < 0.01$, $F = 32.667$). The result is visualized as Figure 20. Except group S4, three groups rated the 400R mock-up most comfortable. For group S4, flat device was evaluated as the most comfortable mock-up and the degree of subject comfort level decreased as the curvature increased. Overall, four groups have unique patterns in terms of comfort level, which means each group has its own preference.

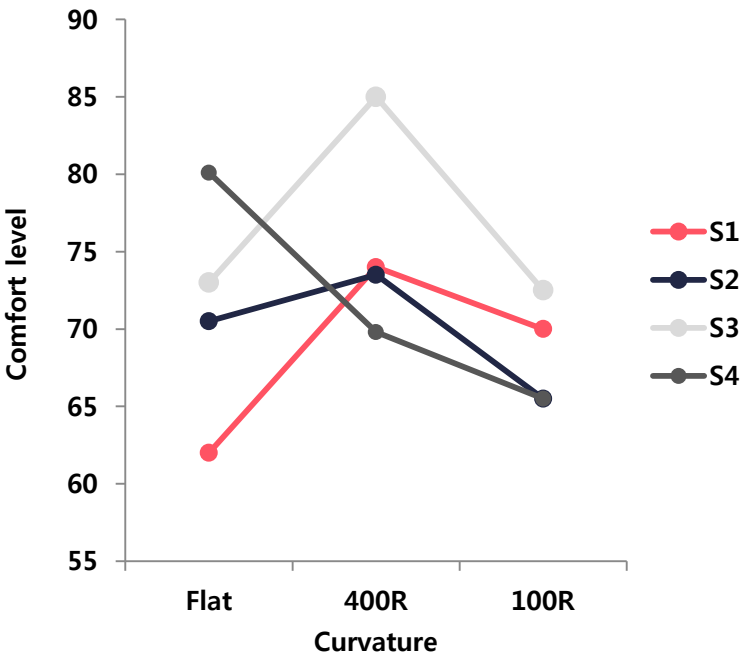

Figure 20. Relationship between curvature and comfort level for each group

4.6 Muscle activities of levels for each task

In order to determine the effect of the location of the targets and the direction of the thumb movements when tapping and dragging, respectively, the ANOVA tests were performed on % MVC for each task ($\alpha = 0.05$). In this section, the typing task was excluded in the section because the ANOVA test on average %MVC values of each word was too simple to analyze the task.

4.6.1 Tapping task

For tapping tasks, there were five targets differentiated from the location as shown at Figure 6. Through the ANOVA test, it is confirmed that the use of the muscles were varied by the location of the target regardless of their hand size when the participants reached to each target. According to the result of post hoc tests, reaching to the target 3 required significantly higher muscle activity in general, but rest targets showed similar degrees in %MVC to reach.

4.6.2 Dragging task

When the participants dragged their thumb on the surface of the mock-ups, different muscle use patterns were observed in the directions of the movement. In the case of the dragging task, the result was little more complicated than the tapping task. SW direction, which is the most natural direction when dragging, activates muscles most in contrast to the others. The directions to S, NW and N consumed muscles least while dragging. For each group classified by hand size,

the values of %MVC were varied by the directions, except group A3 having smallest size of hand (p=0.55); the small-hand group uniformly uses the muscles regardless of the direction.

Regarding individual muscle, there was no statistically significant difference in the direction of drag operations excluding OP; moving directions varies in muscle usage of OP. OP was utilized by moving direction southwestward most and westward next most for all groups in common, and southeastward movement required least muscle activity to OP. The other directions did not clearly show consistent orders of %MVC values on OP. This result shows OP takes decisive effect by the dragging direction dissimilar to ADM, FPL or FDP.

Table 21. Result of analysis of variance on muscle activity between the locations of the target for tapping task

%MVC, Mean (Standard deviation)

	Level (The Location of Target)					F	Scheffe test
	1	2	3	4	5		
Tapping task	6.198 (4.22)	6.262 (4.86)	14.263 (14.16)	7.581 (5.05)	7.457 (7.12)	32.06**	Target 3 >> Target 1, 2, 4, 5

** $p < 0.01$

Table 22. Result of analysis of variance on muscle activity between the directions of the thumb movement for dragging task

%MVC, Mean (Standard deviation)

	Level (The Direction of the Thumb movement)								F	Scheffe test
	SW	S	SE	E	NE	N	NW	W		
Dragging task	11.363 (8.49)	7.614 (5.53)	8.231 (6.67)	8.860 (6.39)	8.338 (5.92)	6.696 (4.72)	7.562 (5.17)	9.542 (7.79)	8.916**	Direction SW > Direction W,E,NE, SE > Direction S, NW, N

** $p < 0.01$

Table 23. Result of analysis of variance on muscle activity of Opponens Pollicis (OP) among the directions for each groups classified by the hand size

%MVC, Mean (Standard deviation)

Group by hand size	Level (Direction)								F	Scheffe test
	SW	S	SE	E	NE	N	NW	W		
A1	19.927 (8.51)	6.026 (3.5152)	6.160 (3.546)	9.619 (5.55)	9.789 (5.64)	5.321 (2.926)	9.708 (6.143)	16.847 (10.18)	15.233**	Direction SW, W > Direction NE, NW, E > Direction SE, S, N
A2	23.928 (6.94)	9.176 (3.27)	6.926 (3.66)	11.002 (5.86)	14.652 (6.69)	8.049 (4.35)	9.229 (4.96)	19.271 (8.63)	19.254**	Direction SW > Direction W, NE >Direction E, NW, S, N> Direction SE
A3	22.095 (7.57)	12.050 (2.91)	6.632 (3.35)	11.407 (3.64)	13.912 (3.34)	8.982 (3.41)	8.822 (3.51)	20.401 (7.79)	8.003**	Direction SW, W > Direction NE, S, E, N, NW, SE

** $p < 0.01$

Chapter 5. Conclusion and Discussion

This study aims to investigate the effect of curvature of touchscreen device on comfort having the curvatures of 400R and 100R as well as flat device. The effect of hand anthropometry which determines size and shape of the hand on comfort was also inquired after classifying the hands of Korean population, aged from 20 to 80, by size and shape. The muscles located at the upper limb and the hand, ADM, OP, FDP, and FPL, were defined as the relevant muscles to operate touchscreen with one hand. It was assumed that the basic tasks were tapping, typing and dragging.

According to the statistical analysis on the anthropometric data set related to hand with 342 of the representative population sample, there are three distinctive groups by the hand size and four distinctive groups by hand shape in Korea. When designing uni-size handheld devices, the physical, physiological and psychological characteristics of each group should be considered.

Generally, each muscle was utilized ranged from 4.8% to 12.2% of MVC, which is corresponding range of low level exertion. This means sustained or prolonged intermittent use of touchscreen device for hours can induce local muscle fatigue with high probability (Jørgensen et al., 1988). The people living in the digital world are highly exposed by risks of hand muscle fatigue even not in the office or the work place.

Going to in detail, the effect of curvature on the muscles was not significant when performing all tasks; each device showed no

difference on %MVC values of ADM, OP, FDP and FPL, except one case. The extent of muscle activity of FDP, the muscle related to grip the device, had significant difference among the curvatures for the dragging task, in particular, only for the group with small hand. That is, curvature does matter to grip only for small hand users when they drag the thumb, one-handed, along the touchscreen devices. In this case, the moderately curved device (400R) was the best in the sense of activating muscle least. Despite of this, the curvature between 400R and 100R will possibly be better than 400R based on the result of the curve fitting model.

On the other hand, subjective comfort level was influenced by curvature. The 400R-devicee was more comfortable than 100R-device which was more comfortable than flat device proved by the result of the survey.

A part of hypothesis $H_{1,}$ $H_{1A,}$ was rejected, except the case of FDP for small hand group when dragging thumb.

H_{1A}: Curvature of the handheld touchscreen smartphone devices affects objective comfort (muscle activity).

However, the other part of hypothesis 1(H_{1B}) was accepted.

H_{1B}: Curvature of the handheld touchscreen smartphone devices affects subjective comfort.

Also, the degree of muscle activity in totality for each group hand size varies with curvature and each curvature activates the individual muscle differently; the group A2 having mid-size hand utilized the

muscles most, except FPL. The group A3 activated FPL significantly more than other A1 and A2. Group A1 used muscles least for all tasks, overall. It was same with individual muscle excluding FDP which was least used by A3.

The cases distinguished by curvature, the result was same. When using all mock-ups, the muscle activities of group A1 were significantly less than rest groups and this was consistent to the previous result that curvature did not give significant effect on muscle usage.

As well as muscle activity, comfort level was significantly different among the groups; comfort levels were evaluated in the descending order of A2, A3 and A1.

When curvature and comfort level got together, interactions were found that the 100R-mock-up received analogous rating in comfort among the groups by hand size and flat device did the other way around. For 400R mock-up, the group A2 evaluated comfort level more generously than the other groups and A1 and A3 did almost identically with lower comfort level.

Summarizing these, the next null hypothesis H_{2A} was accepted.

H_{2A}: Size of the hand affects subjective and objective comfort when using the handheld touchscreen devices

Overall muscle use regardless of curvature is different among the groups; S1 possessing smaller palm activates muscles least and S4 of which members have skinny hand activates them most. S2 with bigger palm and S3 having short thumb are statistically identical in overall

muscle usage. For each muscle, all groups do not show same propensity of muscle activity. Especially, S3 and S4 never belong to the same side and this means the two groups need to be treated different. Also, the short thumb users (S3) utilize muscles, related to supporting the device by the little finger and operating thumb, less than the others, but they grip more firmly.

For each curvature, the same difference was found. The overall muscle activity of S3 and S4 are always at the opposite side and S3 uses the muscles less than S4 for all curvatures. This supports that users who belongs to S3 and S4 have different muscle operation mechanisms.

Same as the groups classified by the hand size, the groups by the hand shape did not evaluate comfort homogenously. Therefore, the next null hypothesis H_{2B} was accepted, too.

H_{2B}: Shape of the hand affects subjective and objective comfort when using the handheld touchscreen devices

Interest thing is that high level of muscle activation is somehow related to high comfort level; participants who belong to A1 show least muscle activity and least comfort evaluation. Also, S4 of which members utilizes the muscles most rated most generously.

Taking a close look at the tapping task, it is confirmed that the participants uses muscles more to reach target 3 regardless of their hand size. This means that targets which are frequently used should not be located at the lower-left corner of the device where target 3 was located. Also, different muscle use patterns for OP were observed with the eight

directions of thumb movement during the dragging task performance. Normally, southeastward movement required most even though the direction was most natural to drag holding the device in one hand. When designing user interface or a similar type of handheld device, these facts should be considered to avoid muscle fatigue. Lastly, the overall values of %MVC were not different by dragging direction for small-hand users, so this can be interpreted that small-hand group has different use pattern in the sense of muscle activity comparing to the groups possessing bigger hand regarding dragging thumb. The groups should be considered differently by product designers.

Integrating the result, the last hypothesis, H_3, was accepted.

H_3: Levels for tapping and dragging tasks influence muscle activity when using the handheld touchscreen devices

The experiment was done having not enough sample sizes for each group and limited aged participants. There is a room to modify the results if it is extended in greater size for each group and wider range of age for participants.

Based on this study, other researches may be carried out. This study excluded muscle fatigue occurrence with limited experiment time and enough break time on purpose. However, with longer experiment time, the local fatigue occurrence might be found, since low level force can induce muscle fatigue (Cifrek et al., 2009). Also, the mock-ups used for the experiment were varied only in curvature, but not in the width, depth or length. The variation in size may interact with curvature and other factors, so this is able to be verified later.

This study warns the considerable risk of getting fatigue, but referring to the results, it will help on designing the handheld touchscreen device which is used by a single hand. Also, the results indicate that considering user interface of tasks may be dominant in designing the particular device rather than curvature. Nevertheless, personal flexible display is currently available in the real world, so researches related to the effects of curvature should be done in the near future.

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국문 초록

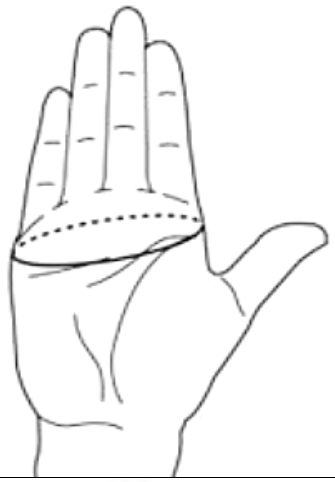
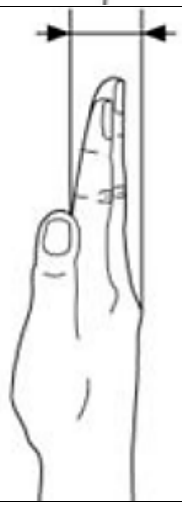
신체적 편안함은 휴대용 기기의 설계 시 최우선적으로 고려해야 하는 요소 중 하나이다. 최근, 플렉시블 디스플레이 기술의 발전과 함께 화면이 휘어있는 터치스크린 기기들이 출시되었으나, 아직 곡면 화면의 신체적 편안함에 대한 효과는 검증된 바가 없다. 신체적 편안함에 관련된 인간공학 관련 요소는 인체 측정학적 요소와 생리학적 요소 두 가지로 구분할 수 있다. 이는 터치스크린 휴대용 기기의 인간공학적 설계를 위해 손의 크기와 모양, 그리고 근육 사용량에 대한 사용자 집단의 다양성을 고려하는 것이 반드시 필요하다는 것을 의미한다. 통계적으로 한국인 집단은 손의 크기와 모양에 있어 큰 다양성을 보인다는 것으로 분석되었다. 또한 이전 연구에서 터치스크린 스마트폰 사용자들의 약 1/3 은 한 손으로 기기를 사용하는 것이 관찰되었다. 본 연구는 터치스크린 휴대용 기기를 한 손으로 사용하는 경우 손에 대한 인체 측정학적 요소와 화면의 곡률이 신체적 편안함에 미치는 영향을 밝히는 것을 목적으로 하였다. 신체적 편안함은 피실험자가 3 가지 과업 -탭, 드래그, 문자 입력- 을 3 가지 실물 모형 -평평한 화면, 400R, 100R 의 곡률 화면-을 대상으로 수행할 때 주관적 평가 방법과 객관적 평가 방법을 적용하여 측정되었다. 분석 결과, 화면의 곡률은 주관적인 편안함에는 영향을 미치나 EMG 신호를 통하여 얻은 근육 사용량에 대해서는 유의한 영향을 끼치지 않는 것으로 나타났다. 또한, 손의 크기와 모양은 근육 사용량과 주관적 평가에 통계적으로 유의한 영향을 주는 것으로 분석되었다. 탭 과업에 있어 화면 상 타깃의 위치와 드래그 과업에서 드래그 방향 역시 근육 사용에 유의한 영향을 주는 것으로 보여졌다. 이러한 결과를 바탕으로 본 연구는 터치스크린 휴대용 기기를 한 손으로 사용하는 경우, 화면 상의 사용자 인터페이스가 화면 곡률과 같은 하드웨어적 요소보다 손의 편안함에 대해 더 중요한 요소가 될 수 있다는 가능성을 제시한다.

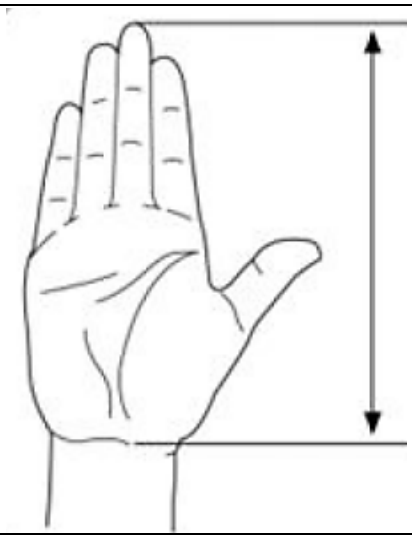
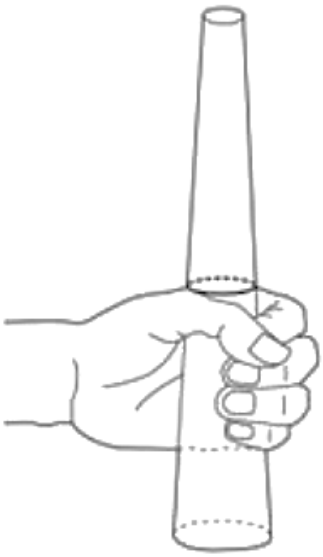
핵심어: 터치스크린 휴대 기기, 곡률, 신체적 편안함, EMG, 사용자 인터페이스, 엄지의 사용

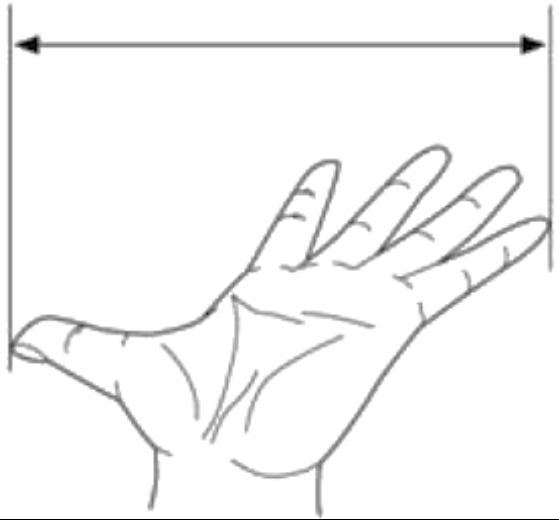
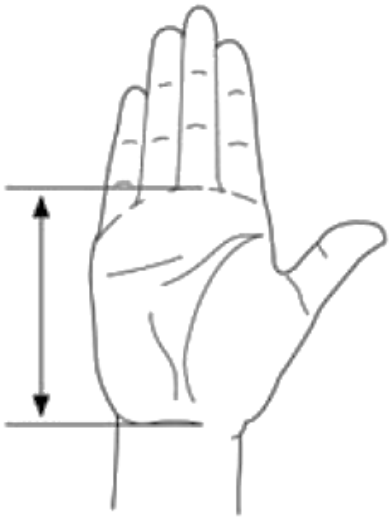
학번: 2012-21062

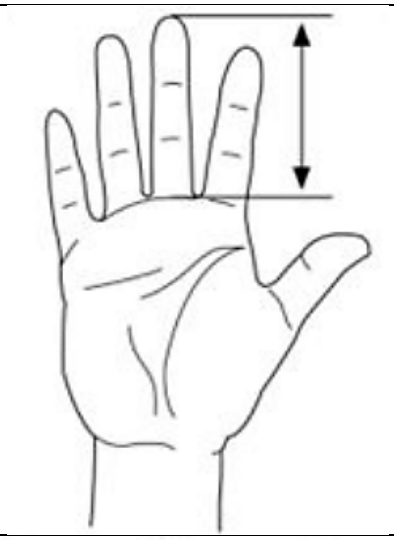
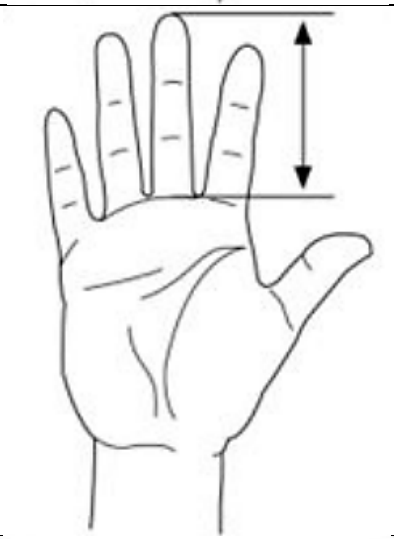
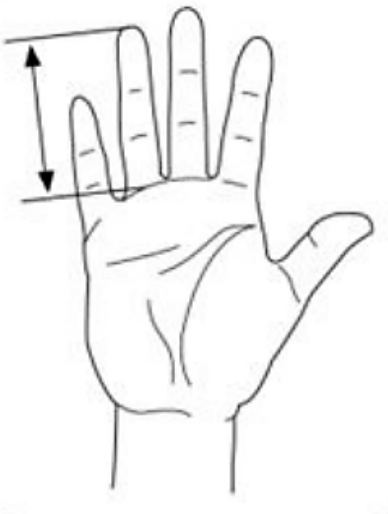
APPENDICES

Appendix A. Hand Dimension Description

Hand dimension	Description
Hand Circumference	
Hand Breadth	
Hand Depth	

Hand Length	
Inner Grip Circumference	
Radial styloid - Thumb fingertip length	

Maximum Finger Span Breadth	
Palm Length Perpendicular	
Finger Length (Thumb	

Finger Length (Index Finger)	
Finger Length (Medius Finger)	
Finger Length (Ring Finger)	

Finger Length (Little Finger)	
Capitate – Finger First Crease Line Length (Thumb)	
Capitate – Finger First Crease Line Length (Index Finger)	

Capitate – Finger First Crease Line Length (Medius Finger)	
Capitate – Finger First Crease Line Length (Ring Finger)	
Capitate – Finger First Crease Line Length (Little Finger)	

Appendix B. EMG System Specification

WEMG-8 (LXN5308)	
Data Transmission	Wireless
EMG Channels	8
Polarity	Bi-polar
Sensitivity	5,000 μV / Half window (Max.) 312.5 μV / Half window (Min.) 5 steps control by S/W
Bandwidth	13~ 430 Hz (-dB)
Band Elimination Filter Frequency	60Hz
CMRR	90dB (Min.)
Internal Noise Level	20 μVrms (Max.)

Appendix C. Experimental Sheet

Participant #		Age	
Sex	Male / Female		
Preferred hand		Right / Left	
Hand		(mm)	
Hand Circumference			
Hand Breadth			
Hand Depth			
Hand Length			
Inner Grip Circumference			
Radial styloid-thumb fingertip length			
maximum finger span breadth			
Palm length perpendicular			
Finger length	Thumb		
	Index finger		
	Medius finger		
	Ring finger		
	Little finger		
Capitate-Finger first crease line length	Thumb		
	Index finger		
	Medius finger		
	Ring finger		
	Little finger		

Sample #	① ② ③
Satisfaction Level	/ 100
Comfort Score	/ 100

Comment	

Sample #	① ② ③
Satisfaction Level	/ 100
Comfort Score	/ 100

Comment	

Sample #	① ② ③
Satisfaction Level	/ 100
Comfort Score	/ 100

Comment	

Discriminant Analysis Results	
Actual scale	
Normalized scale	

Experiment duration

Max. VC	ADM	OP	FDP	FPL
Before				
After				

Appendix D. Descriptive Statistics for Hand Dimensions of Participants

		Min.	Max.	Mean	Std. Deviation
Hand Circumference		15.00	21.80	18.962	1.6455
Hand Breadth		71.20	87.33	78.565	4.2667
Hand Depth		20.53	32.08	27.360	3.2139
Inner Grip Circumference		28.63	40.78	33.798	2.9278
Hand Length		155.82	199.36	179.85	11.604
Radial styloid-thumb fingertip length		96.38	124.10	112.09	6.7926
Maximum finger span breadth		119.00	233.00	203.31	27.474
Palm length perpendicular		90.30	116.79	104.14	7.0007
Capitate – Finger First crease line length	Thumb	65.38	76.71	71.124	3.9506
	Index finger	97.32	119.70	108.82	6.0127
	Medius finger	95.52	121.90	107.98	6.6239
	Ring finger	89.08	115.66	102.78	6.7996
	Little finger	81.76	108.13	94.188	6.5006
Finger length	Thumb	52.52	69.85	62.215	4.2784
	Index finger	61.73	80.28	70.669	5.8507
	Medius finger	66.26	85.11	77.351	5.5798
	Ring finger	59.45	79.41	71.835	5.8826
	Little finger	47.86	64.84	56.783	5.0918

Appendix E. The Result of ANOVA Test

Analysis of variance on muscle activities between curvatures for overall muscle activity

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	16.086	2	8.043	.171	.843
Within Groups	135602.259	2877	47.133		
Total	135618.345	2879			

Analysis of variance on muscle activities between curvatures for ADM

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	9.763	2	4.881	.181	.835
Within Groups	19352.553	717	26.991		
Total	19362.316	719			

Analysis of variance on muscle activities between curvatures for OP

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	32.624	2	16.312	.185	.832
Within Groups	63376.914	717	88.392		
Total	63409.538	719			

Analysis of variance on muscle activities between curvatures for FDP

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	25.089	2	12.544	1.067	.345
Within Groups	8428.010	717	11.755		
Total	8453.099	719			

Analysis of variance on muscle activities between curvatures for FPL

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	11.160	2	5.580	.187	.829
Within Groups	21384.235	717	29.825		
Total	21395.394	719			

Analysis of variance on muscle activities between curvatures for FDP for the small hand group during the dragging task

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	8.975	2	4.487	9.641	.000
Within Groups	20.945	45	.465		
Total	29.919	47			

Analysis of variance on subjective comfort level between curvatures

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	49777.778	2	24888.889	143.073	.000
Within Groups	500480.000	2877	173.959		
Total	550257.778	2879			

Analysis of variance on muscle activities between the groups classified by the hand size in totality

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	7211.760	2	3605.880	66.334	.000
Within Groups	156392.457	2877	54.360		
Total	163604.217	2879			

Analysis of variance on muscle activities between the groups classified by the hand size for ADM

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	5923.490	2	2961.745	126.871	.000
Within Groups	16737.976	717	23.344		
Total	22661.466	719			

Analysis of variance on muscle activities between the groups classified by the hand size for OP

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	1480.899	2	740.450	6.939	.001
Within Groups	76504.594	717	106.701		
Total	77985.493	719			

Analysis of variance on muscle activities between the groups classified by the hand size for FDP

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	381.672	2	190.836	15.561	.000
Within Groups	8792.925	717	12.263		
Total	9174.597	719			

Analysis of variance on muscle activities between the groups classified by the hand size for FPL

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	2360.909	2	1180.454	36.378	.000
Within Groups	23266.422	717	32.450		
Total	25627.331	719			

Analysis of variance on muscle activities between the groups classified by the hand size for mock-up, flat.

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	3068.950	2	1534.475	27.154	.000
Within Groups	54080.287	957	56.510		
Total	57149.237	959			

Analysis of variance on muscle activities between the groups classified by the hand size for mock-up, 400R.

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	1680.047	2	840.023	15.126	.000
Within Groups	53145.326	957	55.533		
Total	54825.373	959			

Analysis of variance on muscle activities between the groups classified by the hand size for mock-up, 100R.

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	2623.647	2	1311.823	25.628	.000
Within Groups	48986.487	957	51.188		
Total	51610.134	959			

Analysis of variance on subjective comfort level between the groups classified by the hand size

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	46689.524	2	23344.762	133.374	.000
Within Groups	503568.254	2877	175.032		
Total	550257.778	2879			

Result of analysis of variance on muscle activity between the groups classified by the hand shape in totality

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	3540.3829	3	1180.1276	21.204335	.000
Within Groups	160063.83	2876	55.655019		
Total	163604.22	2879			

Result of analysis of variance on muscle activity between the groups classified for ADM

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	1410.0182	3	470.00607	15.835361	.000
Within Groups	21251.448	716	29.680793		
Total	22661.466	719			

Result of analysis of variance on muscle activity between the groups classified for OP

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	9739.3461	3	3246.4487	34.059905	.000
Within Groups	68246.147	716	95.315848		
Total	77985.493	719			

Result of analysis of variance on muscle activity between the groups classified for FDP

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	1989.6707	3	663.22357	66.092272	.000
Within Groups	7184.9259	716	10.034813		
Total	9174.5967	719			

Result of analysis of variance on muscle activity between the groups classified for FPL

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	2572.1056	3	857.36853	26.626322	.000
Within Groups	23055.226	716	32.200036		
Total	25627.331	719			

Result of analysis of variance on muscle activity between the groups classified by the hand shapes for flat mock-up

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	1891.0754	3	630.35847	10.905587	.000
Within Groups	55258.161	956	57.801424		
Total	57149.237	959			

Result of analysis of variance on muscle activity between the groups classified by the hand shapes for 400R mock-up

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	1543.4281	3	514.47604	9.2308773	.000
Within Groups	53281.944	956	55.734251		
Total	54825.373	959			

Result of analysis of variance on muscle activity between the groups classified by the hand shapes for 100R mock-up

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	533.73832	3	177.91277	3.3300042	0.0190537
Within Groups	51076.395	956	53.427192		
Total	51610.134	959			

Result of analysis of variance on comfort level between the groups classified by the hand shapes

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	31739.259	3	10579.753	58.681356	.000
Within Groups	518518.52	2876	180.29156		
Total	550257.78	2879			

Result of analysis of variance on muscle activity between the directions of the thumb movement for dragging task

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	2596.4409	7	370.92012	8.916059	.000
Within Groups	59573.138	1432	41.601354		
Total	62169.579	1439			

Result of analysis of variance on muscle activity between the locations of the target for tapping task

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	8160.6822	4	2040.1705	32.06289	.000
Within Groups	56949.089	895	63.630267		
Total	65109.771	899			

Result of analysis of variance on muscle activity of Opponens Pollicis (OP) among the directions for big-size hand

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	4130.4801	7	590.06858	15.23334	.000
Within Groups	6197.6516	160	38.735322		
Total	10328.132	167			

Result of analysis of variance on muscle activity of Opponens Pollicis (OP) among the directions for mid-size hand

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	4595.9461	7	656.56373	19.254376	.000
Within Groups	4637.5259	136	34.099455		
Total	9233.4721	143			

Result of analysis of variance on muscle activity of Opponens Pollicis (OP) among the directions for small-size hand

%MVC

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	1295.4887	7	185.06981	8.0031718	.000
Within Groups	924.98233	40	23.124558		
Total	2220.471	47			

Appendix F. Curve Fitting Model Summary and Parameter Estimates

Model Summary and Parameter Estimates

Dependent Variable : Comfort Level

Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	0	0.114	1	2686	0.735	73.146	16.484		
Quadratic	0.175	284.464	2	2685	0	68.571	5607.143	-528571.429	
Cubic	0.175	284.464	2	2685	0	68.571	4550	0	-4.23E+07
Compound	0.001	3.229	1	2686	0.072	71.936	3.727		
Exponential	0.001	3.229	1	2686	0.072	71.936	1.316		
Logistic	0.001	3.229	1	2686	0.072	0.014	0.268		

The independent variable is Curvature.