Doctoral Thesis

Ergonomic Design Guidelines for Non-flexible, Foldable, and Rollable Mobile Devices

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Approved by

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28. 12. 2018

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ABSTRACT

Smartphones are mobile devices used daily by people of almost all ages. Therefore, improving these devices from an ergonomic perspective can benefit many people. Similarly, future mobile devices with new displays must be designed from an ergonomic perspective. The purpose of this thesis was to develop ergonomic design guidelines for current non-flexible smartphones as well as future flexible display devices, considering perceived grip comfort, user preference, attractive design, and/or muscle activity. This thesis consists of six studies. The first two studies are on current smartphones with non-flexible displays, and the remaining four studies are on future mobile devices with flexible (foldable and rollable) displays.

Study 1 examined the effects of task (neutral, comfortable, maximum, vertical, and horizontal strokes), phone width (60 and 90 mm), and hand length (small, medium, and large) on grasp, index finger reach zone, discomfort, and muscle activation for smartphone rear interaction. Ninety individuals participated in this study. The grasp was classified into two groups for rear interaction usage. The recommended zone for rear interaction was 8.8–10.1 cm from the bottom and 0.3–2.0 cm to the right of the vertical center line. Horizontal (vertical) strokes deviated from the horizontal axis in the range −10.8° to −13.5° (81.6 to 88.4°). Maximum strokes appeared to be excessive as these caused 43.8% greater discomfort than neutral strokes did. A 90-mm width also appeared to be excessive as it resulted in a 12.3% increase in discomfort relative to the 60-mm width. The small-hand group reported 11.9–18.2% higher discomfort ratings, and the percentage of maximum voluntary exertion of the flexor digitorum superficialis was 6.4% higher.

Study 2 aimed to identify ergonomic forms of non-flexible smartphone by investigating the effects of hand length, four major smartphone dimensions (height, width, thickness, and edge roundness), and mass on one-handed grip comfort and design attractiveness. Seventy-two individuals participated. Study 2 was conducted in three stages. Stage 1 determined the ranges of the four smartphone dimensions suitable for grip comfort. Stage 2 investigated the effects of width and thickness (determined to have the greatest influence) on grip comfort and design attractiveness. Stage 3 investigated the effect of mass on grip comfort and design attractiveness. Phone width was found to significantly influence grip comfort and design attractiveness, and the dimensions of 140×65(or 70)×8×2.5 mm (height×width×thickness×edge roundness) provided higher one-

handed grip comfort and design attractiveness. The selected dimensions were fit with a mass of 122 g and compared within a range of 106–137 g.

Study 3 examined ergonomic forms for mobile foldable display devices in terms of folding/unfolding comfort and preference. Sixty individuals participated. Study 3 was conducted in two stages. In stage 1, suitable screen sizes for five tasks (messaging, calling, texting, web searching, and gaming) were determined. In stage 2, the most preferred folding methods among 14 different bi-folding and tri-folding methods were determined. The device dimension of 140H×60W was preferred for calling, whereas 140H×130W was preferred for web searches and gaming. The most preferred tri-fold concept (140H×198W) utilized Z-shaped screen folding. A trade-off was observed between screen protection and easy screen access.

Study 4 examined the effects of gripping condition, device thickness, and hand length on bimanual grip comfort when using mobile devices with a rollable display. Thirty individuals evaluated three rollable display device prototypes (2, 6, and 10 mm right-side thickness) using three distinct gripping conditions (unrestricted, restricted, and pulp pinch grips). Rollable display devices should have at least 20 mm side bezel width and 10 mm thickness to ensure high grip comfort for bilateral screen pulling. Grip comfort increased as the device thickness was increased. Relative to device thickness, gripping condition greatly influenced bimanual grip comfort.

Study 5 examined the effects of device height (70, 140, and 210 mm), task (web searching, video watching, and E-mail composing), and hand length (small, medium, and large hand groups) on various UX elements associated with using rollable display devices. Thirty individuals participated. Six UX elements (preferred screen width, preferred screen aspect ratio, user satisfaction, grip comfort, portability, design attractiveness, and gripping method) were assessed. Among device height, task, and hand length, device height was the most influential on the UX elements. The 95^{th} percentile preferred screen width of three prototypes (device heights of 210, 140, and 70 mm) was 311.1, 206.2, and 100.0 mm, respectively. The larger the hand length, the wider the preferred screen width. A device (screen) height of 140 (120) mm with a 206.2 mm wide screen improved the overall user experience.

Study 6 examined the effects of gender (15 males and 15 females), device thickness (2T, 6T, and 10T), and pulling duration (0.5s, 1.0s, and 1.5s) on preferred and acceptable pulling forces, muscle activities, and perceived comfort of the upper limbs associated with unrolling rollable displays. Thirty individuals evaluated three rollable display prototypes by laterally pulling each prototype

for three different durations. Preferred and acceptable pulling forces of the upper limbs were measured, and the corresponding muscle activation and perceived comfort were obtained. Pulling duration largely accounted for %MVC of posterior deltoid (PD), flexor carpi radialis (FCR), and extensor carpi radialis (ECR), whereas gender largely accounted for perceived comfort. In consideration of perceived comfort, the device thickness was recommended to be 2 to 6T for both genders. %MVC of PD, FCR, and ECR of the female group was 1.4-2.4 times as high as that of the male group. The perceived comfort of the male group was 1.1-1.3 times higher than that of the female group. Overall, 6T was the best thickness. Users preferred a shorter pulling duration with a higher level of muscle activation than a longer pulling duration with a lower level of muscle activation to unroll the rollable screen.

This work suggested ergonomic design guidelines for non-flexible smartphones and flexible mobile devices. Through these guidelines, basic dimensions and concepts for current and future mobile devices can be specified. In future studies, it is necessary to consider the intangible UX for future mobile devices by investigating the GUI based on the PUI proposed in this study.

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Chapter 1. Introduction

1.1. Background

With the advances in electronics and display technology, the role of mobile phones has evolved from simply making calls to performing diverse tasks (e.g., web searching, video watching, and E-mailing). In addition to improvements in hardware performance (e.g., size and resolution of display and CPU/RAM processing speed), next-generation displays have been developed. Curved displays are advantageous in terms of legibility and immersion compared to flat displays (Park et al., 2017), and diverse curved display devices have been already released. Recently, flexible displays have begun to be developed as next-generation displays. Diverse types of display devices with flexible displays are expected to be commercialized in the near future (Figure 1.1). Compact mobile devices featuring large flexible screens are expected to follow flat and curved display devices shortly (Huitema et al., 2008; Davies, 2016; Prabhu, 2017; Mordor intelligence, 2018; Smith, 2018). Ergonomic studies on flat and curved smartphones have been intensively performed. Conversely, there exist few studies on flexible display devices as these devices are still in the initial development stage.

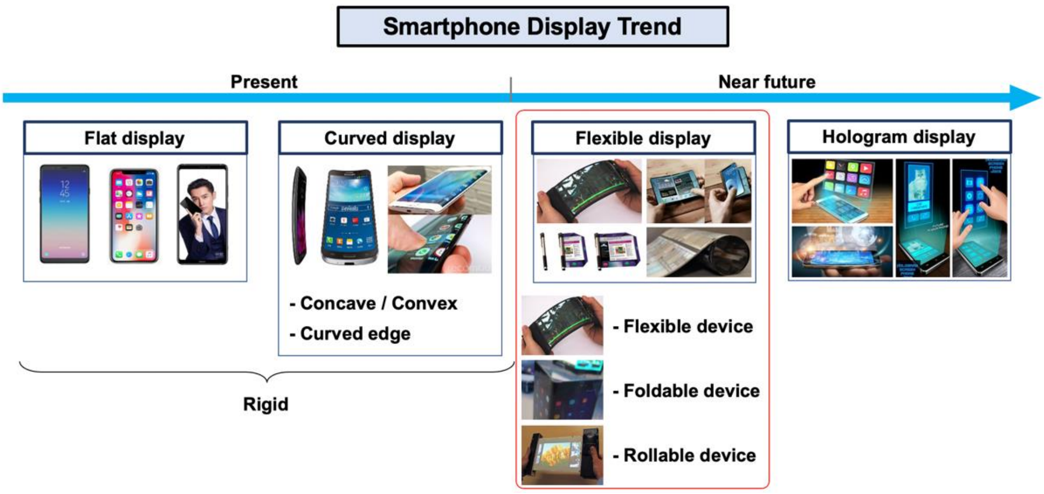

Figure 1.1 Trend of smartphone displays (Huitema et al., 2008; Davies, 2016; Mordor intelligence, 2018; Prabhu, 2017; Smith, 2018)

To improve the completeness of a product, not only the product performance but also the user interface (UI) and user experience (UX) must be improved. Mobile devices contain inputs (e.g., buttons or touch screen), and smartphones have extra input methods on their side (e.g., home button or volume buttons) and rear (e.g., finger-print sensor) surfaces. To be competitive in the market, smartphones should therefore be designed to provide comfortable physical/graphical UI and UX. For example, when designing a physical UI, the range of motion of the fingers should be considered to accommodate a wide range of individuals (as addressed in Chapter 3).

When using a hand-held device, users select a grip posture considering the object, the task, and their hand (Cutkosky 1989). The term “object” represents specifications such as size, shape, or weight, which can affect grip posture. For a simple example, grip postures with a pen and a hammer are different. “Task” means that grip posture can be different even with the same object. For example, grip postures for chopping an apple and peeling an apple are different. “Hand” means that the size, property, or thickness (obesity) of hand can affect the grip posture. For example, people with large hands can grip the whole perimeter of a bar, but people with small hands cannot. As object, task, and hand can affect grip comfort, these three factors should be considered when designing any hand-held device, including mobile devices.

There exist diverse hand anthropometric dimensions related to grip comfort. In a study by Chowdhury & Kanetkar (2017), the preferred mobile phone size was investigated based on the hand anthropometry and mobile handiness (perception about ease of holding/gripping, ease of task execution, and usefulness of the physical product). Four hand dimensions (hand length, palm length, hand breadth with thumb, and hand breadth without thumb) were used as independent variables. There were high correlations among these four hand dimensions (≥ 0.95). In previous studies on hand-held devices, including on mobile devices, hand length was commonly considered (Kong and Lowe, 2005; Otten, Karn, & Parsons, 2013).

For mobile design, grip comfort should be one of the critical design factors (Wickens, Gordon, Liu, & Lee, 1998; Ahn, Kwon, Jin, Kim, & Yun, 2014), as should hand tools (Kuijt-Evers, Groenesteijn, de Looze & Vink, 2004; Kong, Kim, Lee, & Jung, 2012). In addition, users choose a different grip type for each task due to the various functions of a smartphone (Kim et al., 2006). For example, users use whole fingers to grip the body of the device during calls (Choi, Jung, Park, & You, 2017). In the case of taking photos, however, they use their thumb (or index finger) to push the shutter button, so they grip the device with all fingers except the thumb (or index finger). Therefore, grip comfort with the smartphone in various tasks should be investigated.

Formative evaluation is an effective method to define the product design during the prototype design stage. Formative evaluation is a collection of ‘fine-and-fix’ usability methods to identify the problems and find better designs before release, whereas summative evaluation is the method of evaluating the usability of the final design (Redish et al., 2002; Rohn et al., 2002; Ji, Park, Lee,

& Yun, 2006). Formative evaluations cover a variety of evaluation methods, such as expert evaluation (e.g., heuristic evaluation), model evaluation (e.g., user activities analysis), user evaluation (e.g., verbal protocols), and evaluation location (e.g., laboratory experiments) (Ji, Park, Lee, & Yun, 2006). Because future display devices have not yet been released, their concepts and designs can be effectively improved through formative evaluation in terms of usability (Ji, Park, Lee, & Yun, 2006).

To summarize, ergonomic design guidelines for smartphones and future smart devices should be suggested in advance to effectively and efficiently develop and improve them.

1.2. Objective and Specific Aims

The objective of this thesis was to develop tangible UX/UI design guidelines for current non-flexible smartphones as well as future flexible display devices considering perceived grip comfort, user preference, attractive design, and/or muscle activities. To achieve this, six studies were conducted. The specific aims were as follows:

(1) Investigate the effects of interaction task type, device width, and hand length on smartphone grasp, index finger reach zone, subjective discomfort, and muscle activation related to smartphone rear interaction using the index finger (Chapter 2 on non-flexible smartphones).

(2) Compare the rear interaction zones of 140 smartphone models with Lee et al. (2016)'s recommended zone (Chapter 2 on non-flexible smartphones).

(3) Investigate the effect of smartphone width and height on the location of rear interaction zones (Chapter 2 on non-flexible smartphones).

(4) Identify ergonomic smartphone forms by investigating the effects of hand length and four major smartphone dimensions - height, width, thickness, and edge roundness (Chapter 3 on non-flexible smartphones).

(5) Investigate the interactive effects of hand length, device height, and device width on grip comfort and design attractiveness (Chapter 3 on non-flexible smartphones).

(6) Investigate the effects of hand length and smartphone mass on grip comfort and design attractiveness (Chapter 3 on non-flexible smartphones).

(7) Determine suitable screen sizes for five representative smartphone tasks (instant messaging, calling, texting, web searching, and gaming) on mobile foldable display devices considering a wide range of hand lengths (Chapter 4 on foldable smart devices).

(8) Determine the most preferable folding method among five folding methods (Chapter 4 on foldable smart devices).

(9) Investigate the effects of gripping condition, device thickness, and hand length on the gripped region of each side bezel and the grip comfort of each hand for rollable display

devices (Chapter 5 on rollable smart devices).

(10) Investigate the effects of device height, task, and hand length on various UX elements (preferred screen width, preferred screen aspect ratio, user satisfaction, grip comfort, design attractiveness, and gripping method) for rollable display devices (Chapter 6 on rollable smart devices).

1.3. Scope

An overview of the contents of this thesis is shown in Figure 1.2.

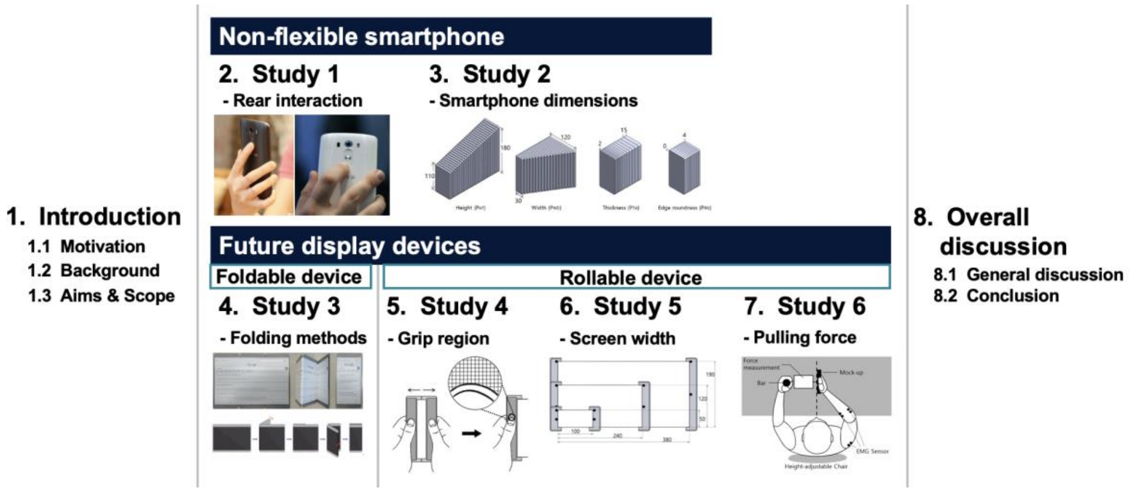

Figure 1.2 Overview of the contents of this thesis

Six different studies are included in this thesis, and the independent variables of all studies were defined based on object, task, and hand (Figure 1.3). In the case of object, various dimensions (e.g., height, width, thickness, and edge roundness) were selectively used to meet the scope of each study. In the case of task, various smartphone tasks ranging from the basic ones, such as touch, scrolling, and unrolling (for rollable displays), to the practical ones, such as searching, video watching, and E-mailing, were selectively used to meet the scope of each study. In the case of hand, hand length was used as an independent variable. Although there are many other hand-related dimensions, such as hand breadth and finger length, because hand length is significantly correlated with hand breadth and finger length (Dey & Kapoor, 2015; Xiong & Muraki, 2016), hand length was selected to differentiate diverse hands.

In this thesis, various factors were measured as the dependent variables (Figure 1.3). Under physical interface, index finger reach zone, gripping method, preferred dimensions, grip region, preferred screen width, and preferred/acceptable pulling force were included, and these can be used as ergonomic design guidelines. In the case of subjective rating, perceived grip comfort was rated on a 100 mm visual analog scale (VAS), and other factors (e.g., design attractiveness, and portability) were obtained using either a 100 mm VAS or 7-point scale. In the case of physiological measurement, muscle activation (using electromyography (EMG)) was measured, and %MVC was calculated for analysis.

An outline of the six studies is illustrated in Figure 1.3.

Target & Topic	IVs: Hand	IVs: Object	IVs: Task	DVs: Physical interface	DVs: Gripping method	DVs: Subjective rating	DVs: Physiological measurement
Non-flexible smartphone							
[Study 1] Rear interaction	Hand length	Device width	Task type	Index finger reach zone	Gripping method	Subjective discomfort	Muscle activation
[Study 2] Smartphone dimensions	Hand length	Four Dimensions		Preferred dimension		Grip comfort; Design attractiveness	
Future display device							
Foldable device							
[Study 3] Folding methods	Hand length	Folding method				Grip comfort; Preferred Folding method	
Rollable device							
[Study 4] Grip region	Hand length	Device thickness	Grip type	Grip region		Grip comfort	
[Study 5] Preferred screen width	Hand length	Device height	Task type	Preferred Screen width	Gripping method	Grip comfort; Portability and Design attractiveness; User satisfaction	
[Study 6] Pulling force	Gender	Device height	Pulling duration	Preferred Pulling force; Acceptable Pulling force		Grip comfort	Muscle activation

Figure 1.3 Outline of experiments on non-flexible smartphones (rear interaction and smartphone dimensions) and future display devices (foldable and rollable).

1.4. Dissertation Outline

This paper consists of the following eight chapters:

Chapter 1 discusses the overall concepts, objectives, and scope of this study.

Chapter 2 presents a study investigating the effects of interaction task type, device width, and hand length on smartphone grasp, index finger reach zone, subjective discomfort, and muscle activation related to smartphone rear interaction using the index finger.

Chapter 3 presents a study investigating the effects of hand length, four major smartphone dimensions, and smartphone mass on grip comfort and design attractiveness.

Chapter 4 presents a study investigating the effects of hand length and folding method on comfort and preference for mobile foldable display devices.

Chapter 5 presents a study investigating the effects of gripping condition, device thickness, and hand length on bimanual grip comfort when using mobile devices with rollable displays.

Chapter 6 presents a study investigating the effects of device height, task, and hand length on various UX elements associated with using rollable display devices.

Chapter 7 presents a study investigating the effects of gender, device thickness, and pulling duration on preferred and acceptable pulling forces, muscle activities, and perceived discomfort of the upper limbs associated with unrolling rollable displays.

Chapter 8 summarizes the major findings of the six studies and suggests ergonomic design guidelines for non-flexible smartphones and future display devices.

Chapter 2. [Study 1] Non-flexible Smartphones: Rear Interactions

2.1. Introduction[1]

Smartphones have become essential for diverse ethnic and age groups. Since the introduction of the Apple iPhone™ (Apple, Cupertino, CA, USA) in 2007, the smartphone market has grown rapidly. Smartphone penetration rates in 20 countries exceeded 70% in 2015, among which five countries, including South Korea, even surpassed 80% (Digieco 2015). Overall, 72.4% of smartphone users in South Korea considered smartphone exterior features (e.g. design, device size, and image quality) when purchasing their smartphone (KISA 2015). In order to develop an ergonomic smartphone, the characteristics of diverse users (e.g. hand anthropometry and natural grasps) need to be well reflected in the design.

Since smartphones have various usages besides phone calls (web searching, e-mailing, using social network services, note-taking, gaming, and watching videos), large screens are needed. Smartphone screen sizes typically increase in three ways. The first involves rearranging the layout in a limited space while maintaining device width by reducing bezel width, removing or relocating physical buttons (like the home button) on the front to other areas, and/or introducing rear interaction methods. The second approach involves simply increasing the device width (the 'phablet' [phone + tablet] concept). The third approach is a combination of the aforementioned two approaches. Smartphones with foldable displays, which can incorporate a large screen while providing portability, are expected in the near future (Ishii et al. 2012). Indeed, several curved display products, an initial step towards flexible displays, have already been released (e.g. the Samsung Galaxy S6 Edge™, LG G Flex™ series). Smartphones with rear interaction methods (e.g. Pantech Vega™ series, LG G2™ and G3™, Samsung Galaxy S6™) reallocate or duplicate functions of the home and/or side buttons on the rear surface of the device.

The Pantech Vega No.6™ released in 2013 is the first smartphone model that adopted a rear interaction method. Afterwards, many smartphones have adopted rear interaction methods. As of 2016, 138 models of global top 10 smartphone manufacturers (Trendforce, 2016, Harish, 2016), and two recent Google models (Pixel™ and Pixel XL™) provide such interaction methods. A wide screen is preferred for some smartphone tasks such as searching, gaming, and watching

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Part of this chapter was published as a journal paper and an international conference paper.

Lee, S., G. Kyung, J. Lee, S. K. Moon, and K. J. Park, 2016. 'Grasp and index finger reach zone during one-handed smartphone rear interaction: effects of task type, phone width and hand length'. *Ergonomics,* 59(11), 1462-1472.

Lee, S., and G. Kyung, 2017. 'Rear interaction zones of 140 smartphone models vs. ergonomic recommendation'. *Presented in Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 61, No. 1, pp. 1051-1053. Sage CA: Los Angeles, CA: SAGE Publications.

videos. In order to increase the screen size without increasing the overall smartphone size, the front home button, side volume button(s), and/or power buttons are relocated on the rear of the smartphone (Lee et al., 2016). In the case of early smartphone models with a rear interaction function, a physical button added on the rear panel was substituted for the front home button and side volume button(s). Some later smartphone models used a touch sensor and/or a fingerprint sensor to provide additional functions such as screen unlocking and scrolling.

Some studies examined smartphone rear interactions. Wobbrock et al. (2008) and Baudisch and Chu (2009) studied rear interaction performance and gesture. Seipp and Devlin (2014) and Xiao et al. (2013) studied rear interaction gestures. Scott et al. (2010), Schoenleben and Oulasvirta (2013), and Kim et al. (2012) studied keyboard input methods on the rear of a mobile device. According to Löchtefeld et al. (2013), rear interactions can lead to safer and more accurate selections, though slower than front interactions. Yoo et al. (2015), Hakoda et al. (2015), and Lee et al. (2016) measured the range of motion of the index finger during rear interactions.

Although 'grasping' and 'manipulating' (performing interaction tasks) co-occur during smartphone use (e.g. web browsing, picture taking), these two have been not considered in a single study. In addition, smartphone interaction is distinct in that, unlike many other interactions (such as hammering, screwing, scissoring, laparoscopic surgery), the interaction target and the tool for interaction are identical. Napier (1956), as cited in Cutkosky and Wright (1986), classified grasps into two categories ('power grip' for stability and security and 'precision grip' for sensitivity and dexterity) and noted that these two are not mutually exclusive. Typical smartphone use requires these two (stable grasp [power grip] and delicate finger movement [precision grip]). Schlesinger (1919), as cited in Cutkosky and Wright (1986), defined 'lateral pinch' that has both power and precision aspects. This grasp requires the thumb and the index finger, but the roles of the remaining fingers are secondary and not specified. In contrast, more fingers are required for one-handed smartphone interaction to ensure both stability and dexterity while a particular finger (e.g. thumb, index finger) is designated for touch interaction. It thus seems necessary to specify each finger's posture and location relative to other fingers and the device in order to describe smartphone grasp in sufficient detail. In addition, studies on smartphone grasps have been limited to front interaction (e.g. Kim et al. 2006); to the authors' knowledge, there is no study on smartphone grasp during rear interaction. 'Task', 'object geometry' and 'gripper (hand)' can affect grasp (Cutkosky 1989). Smartphone users are likely to use different grasps during rear vs. front interaction as front and rear interactions are different tasks, take place at different areas, and require a different digit for touch input (thumb vs. index finger). Therefore, further investigation of the rear interaction method is warranted regarding the effects of interaction tasks, smartphone shape (e.g. device width) and hand size on grasp.

When designing smartphones, grasps and finger movements should be carefully examined to improve their usability (e.g. in terms of physical or subjective comfort during smartphone use). Otten, Karn, and Parsons (2013) examined the effects of sex, age and hand size on thumb reach envelopes and provided guidelines on the position of the front physical buttons on a cell phone. Im et al. (2010) presented the iso-discomfort area by dividing the front screen of the smart device and evaluating discomfort on each region during thumb interaction. By dividing a 6.4 × 3.7 cm (width × height) touch keyboard on the smartphone into five rows and five columns, Choi, Park and Jung (2013) demonstrated that the second row from the top and the second and fourth columns from the left reduced discomfort during two-hand typing, while discomfort increased in the remaining zones that required far-reaching or over-flexion of the thumb. Similarly, comfortable zones for rear interaction have yet to be determined in order to reduce discomfort during rear interaction.

Inconvenient products can cause musculoskeletal disorders (MSDs). Risk factors for MSDs include high task frequency, long task duration, high exertion level, restricted workspace and unnatural posture (Punnett and Wegman 2004). MSDs can occur at the upper extremities, including fingers (tendonitis, tenosynovitis, De Quervain's Syndrome), wrists (tendonitis, tenosynovitis, and carpal tunnel syndrome [CTS]) and elbows (cubital tunnel syndrome) (Anshel 2005; Chaffin, Andersson, and Martin 2006). MSDs at the fingers can be caused by repeated microtrauma, repeated motion, overuse and extreme postures on the tendon and tendon sheath, all of which can occur during smartphone use. CTS at the wrists can be caused by excessive flexion, extension, repetitive wrist exertions and pressure at the bottom of the palm (Armstrong and Silverstein 1987), among which the last two appear to be more relevant for smart device use. Heavy smartphone use often causes sleep and/or attention deficits, especially for younger adults (Lee et al. 2014), indicating high MSD risks due to smartphone overuse. On average, Korean people use their smartphones daily for 3 h and 39 min (Ryu 2014). Since the touch screen panel is an essential part of the smartphone, the thumbs are required to make precise and fast motor movements, though their dexterity might be much poorer than that of the index or middle finger. Similarly, in the case of the index finger used in smartphone rear interaction, it is necessary to examine its posture from the perspective of over-flexion, over-extension, over-adduction and over-abduction. Ergonomic design of smartphone front/rear interaction is thus required to minimize MSD risks on the wrist, thumb and/or index finger.

The objective of the current study was to investigate the effects of interaction task type, device width, and hand length on smartphone grasp, index finger reach zone, subjective discomfort and muscle activation related to smartphone rear interaction using the index finger. Further, the investigated index finger reach zone was compared with the rear interaction zones of released smartphone models. The findings can be applied to the ergonomic design of smartphone rear interaction.

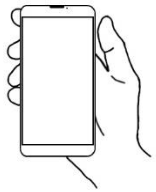
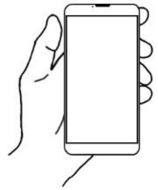
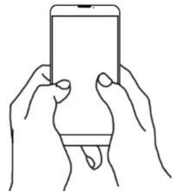
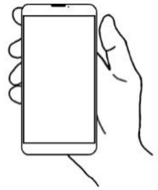
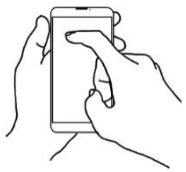
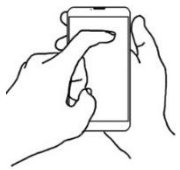
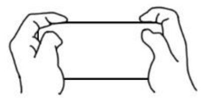
2.2. Material and Methods

Both field and laboratory studies were conducted in the current study. The field study collected data on the grasps used to make vertical strokes on both the front surface of smartphones by the thumb and the rear surface by the index finger. The laboratory study examined index finger rear interaction using vertical strokes and four other strokes (i.e. neutral, comfortable, maximum, and horizontal strokes). Grasps used to make vertical strokes on the rear surface in the laboratory study were compared with those used in the field study. In the laboratory study, the finger reach zone (touch area), subjective discomfort and electromyogram (EMG) of three muscles (first dorsal interosseous [FDI] muscle, flexor digitorum superficialis [FDS] muscle, and extensor digitorum 2 [ED2] muscle) related to the index finger movements were additionally obtained for each task to analyze the main and interaction effects of rear interaction tasks, device width and hand length on such measures.

2.2.1. Participants

Ninety younger individuals (53 men and 37 women) with a mean (SD) age of 22.6 (2.1) years participated in the field study, and 30 younger individuals (11 men and 19 women) with a mean (SD) age of 22.3 (1.1) years participated in the laboratory study. All were recruited from a university population, had used smartphones for at least the past three years, reported that they were healthy and right-handed, and had no wrist MSDs. For the laboratory study, a group of individuals with a wide range of hand lengths were targeted. Prior to the laboratory study, participants were informed of the objective and process of the study and watched a video on the rear interaction method. This study was approved by the local institutional review board.

Table 2.1 Smartphone's primary functions and contexts of use (Expanded from Choi et al., 2013).

Functions (movement)	Operating Condition*		Hand Used			Screen Orientation
Screen on/off (push, touch, swipe)	Sitting without a desk	Standing	Right hand only (for holding and touching)	Left hand only (for holding and touching)	Both hands (for holding and touching)	Portrait
App selection (touch, swipe) Web surfing (touch, swipe)						
Texting (touch) Volume up/down (push, touch, swipe)	Sitting at a desk	Walking	Left hand for holding & right hand for touching	Right hand for holding & left hand for touching		Landscape
Photo taking (push, touch) Calling (touch, swipe)						

* Other operating conditions include using the smartphone while lying on the stomach, back, or side and sitting on the floor.

2.2.2. Design of experiment

The field study collected data on grasps used during front and rear touch interactions on smartphones. Sixty participants scrolled up to view a news article displayed on their smartphones three times using their thumbs. An additional 30 participants scrolled up to view the same news article displayed on an experimental smartphone (Vega LTE-A™, Pantech, Inc.) three times by touching the rear touch area with their index fingers. The laboratory study considered only rear interactions and used a modified version of Choi et al. (2013)'s analysis protocol for a mobile device. According to this protocol, information was collected on the size and weight of 52 smartphones released in South Korea for the previous three years. The mean size was 144.1 × 73.2 × 8.4 mm (length × width × thickness), the width range was 58.6-85.6 mm and the mean (range) mass was 151.9 g (112–210.5 g). After reviewing the collected information on the major functions and contexts of smartphone use (Table 2.1), 'sit at desk (with arms on it)', 'operation with the right hand' and 'portrait screen orientation' were selected as the experimental conditions for smartphone rear interaction. A 5 (task) × 2 (phone width) × 3 (hand length) mixed factorial design was used for the laboratory study. The first independent variable was task type (5 levels, within-subjects factor). It accounted for basic index finger movements during rear interaction: (1) touching the rear area with the index finger in neutral posture (neutral stroke; T_N), (2) comfortably touching the rear area (comfortable stroke; T_C), (3) touching all reachable areas (maximum stroke; T_M), (4) making horizontal lines (horizontal stroke; T_H) and (5) making vertical lines (vertical stroke; T_V). The order of these five tasks was determined using a Latin Square. The phone width (within-subjects factor) had two levels: 60 mm (P_N) and 90 mm (P_W) after consideration of the device widths of the 52 smartphones investigated. Based on the hand data of South Koreans aged between 20 and 50 years (SizeKorea 2004), the hand length (a between-subjects factor) was classified into three levels: small (H_S: ≤165.6 mm [30th percentile]), medium (H_M: 173.6–178.6 mm [45th–55th percentile]) and large (H_L: ≥186.5 mm [70th percentile]). These particular percentile values were selected to ensure a difference of at least 5 mm among the three groups. Stratified sampling was used to obtain an equal sample size per hand group. Dependent variables were the grasps used for rear interaction, the index finger reach zones for each task, the subjective discomfort ratings and EMG readings related to index finger movements.

2.2.3. Data collection and processing

To classify grasps used during front and rear interactions, each finger's position relative to the smartphone was examined using photographs taken in both field and laboratory studies. The length of participants' right hands was measured prior to the laboratory study. Hand length was defined as the distance from the end of the middle finger to the distal wrist crease (SizeKorea 2010). Three EMG electrodes (PolyG-A, Laxtha Co., Korea) were used to measure the activities of three muscles associated with index finger movements. The FDI muscle, between the first and second metacarpal bones of the index finger, engages in index finger abduction. The first electrode for the FDI was attached to the middle of the muscle belly (Kleim, Kleim, and Cramer 2007; Zijdewind and Kernell 1994; Zipp 1982). The FDS muscle engages in index finger flexion. The second electrode for the FDS was attached to the middle of the forearm on the ventral side, approximately three quarters of the distance from the elbow to the wrist (Butler et al. 2005; Criswell 2010; Darling, Cole, and Miller 1994). The ED2 muscle is related to extension of the index finger. The third electrode for the ED2 was attached to the 'mid-forearm at the radial border of the ED' (Leijnse et al. 2008, 3227). Although the first palmar interosseous muscle involves adduction of the index finger, the corresponding electrode was not used because of anticipated skin movement artefact during smartphone grasp (Taylor and Schwarz 1955). EMG was measured for 10 s per task at a sampling rate of 256 Hz.

Two customized epoxy smartphone housings were used in the laboratory study to keep two experimental smartphones equivalent in height and thickness. The height from the top of the screen to the bottom of the housing was 150 mm, and the thickness was 10 mm (Figure 2.1). The weight of the housings was adjusted to ensure that the total weight of the device and the housing was 194 g. The left and right edges of the housing were rounded with a 1-mm radius, and the two corner edges at the bottom were rounded with a 5-mm radius. The smartphones with the housings assembled were used in a flipped-over condition so that their front touch screens could record the regions touched by the index finger during rear interaction. A typical front screen picture was attached to the rear surface of the smartphone housing, which faced the participant during the experiment. Each index finger touch area was saved as an image (in JPG format) using a sketch application (Sketch book, Autodesk, Inc., California, USA). The origin of the coordinates was 90 mm below the top center of the screen (Figure 2.1). Following a sound occurring every second, each participant repeated a 2-s cyclic index finger movement five times per task.

In order to analyze the shape and size of the index finger touch area (Figure 2.1; positive X-values are toward the participant's left side), the touch screen area was divided into 2 × 2 mm cells. A cell was regarded as touched if more than 50% of its area was touched during an interaction task. After each task, the participants reported discomfort felt in their right hands on a 100-mm visual analogue scale (VAS: 0: no discomfort at all, 100: unendurable discomfort). In order to determine %

Figure 2.1 Two experimental smartphones assembled with housing. Smartphone + housing weight = 194 g. housing height = 140 mm, housing width = 10 mm, radius of the bottom corner edges = 10 mm, radius of other edges = 1 mm

maximal voluntary exertion (%MVE) values for abduction, flexion, and extension of the index finger, additional EMG values were measured at maximum voluntary isometric contraction for 10 s. After the first and last 2 s of the collected EMG and MVE data were removed, root mean square values were calculated to obtain %MVE.

To compare the index finger reach zones with the rear interaction zones of released smartphones, model specifications and rear pictures of the global top 10 manufacturers' smartphone models with a rear interaction method were obtained from the Internet. The bottom center of each device was defined as the origin (0, 0) of the XY-coordinates. A Euclidean distance (ED) between the center point of each model's rear interaction zone and the center point of the recommended zone was calculated. The difference between these two center points, (ΔX, ΔY), was also calculated.

2.2.4. Data analysis

Photographs of smartphone grasps taken during field and laboratory studies were classified by examining each finger's position relative to the phone. The index finger touch areas were compared by task, device width and hand length. The center point and X/Y ranges of each touch area were calculated. In the case of $_{TH}$ and T_V, the slope of touched cells from the X-axis (with counter clockwise positions representing positive angles) and the 95% confidence interval (CI) of the slope were calculated using simple linear regression. In addition, a rectangle enclosing the 30 centers of the touch areas (one from each treatment condition) was compared with the rear touch locations adopted by six commercial smartphones. A three-way mixed factor analysis of variance (ANOVA) was used for both subjective discomfort and %MVE data, with post hoc pairwise comparisons done using Tukey's honest significant difference test.

In comparison part, after smartphone width (W) and height (H) data were divided into three groups using the K-Means clustering method, each smartphone group's mean (SD) width and height were calculated. One-way ANOVA) was used to examine the effect of phone group on the location of rear interaction zones. Rear interaction zones of each group were depicted on the XY-coordinates. Statistical analyses were done using JMP™ (v. 11, SAS Institute Inc., NC, USA), with significance concluded at $p < 0.05$.

2.3. Results

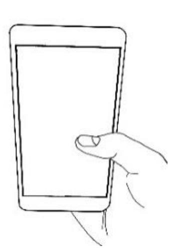
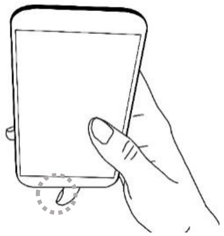
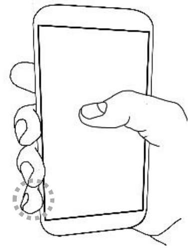
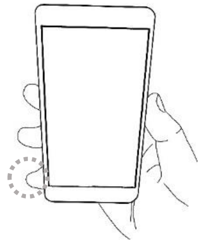
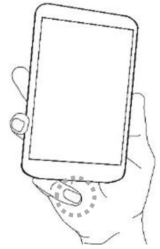
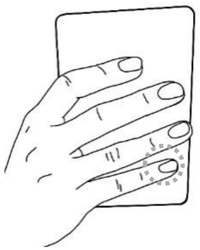
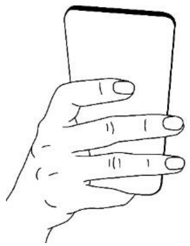
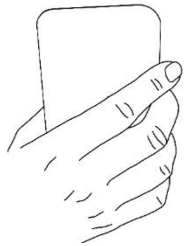
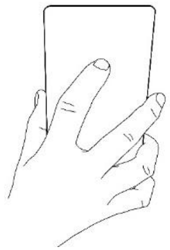
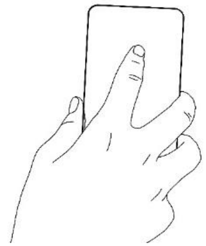
2.3.1. Grasp

Grasps examined for both front and rear interactions differed by the little finger's position. Three different grasps were identified for front interactions (Table 2.2): the little finger on the rear surface (55.0%), the little finger supporting the bottom (36.7%) and the little finger on the lateral side (8.3%). One grasp (holding the lateral sides) was predominantly used for rear interactions (96.7% of cases). All 30 participants in the field study selected this grasp, and only two of 30 participants in the laboratory study used a different grasp (supporting the bottom using the little finger; Table 2.2).

2.3.2. Index finger reach zone

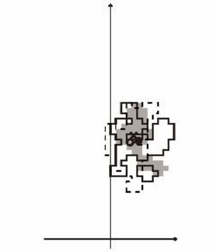
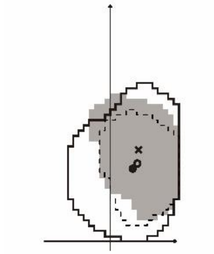
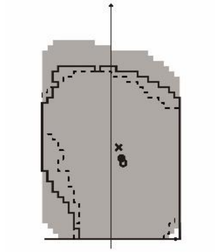
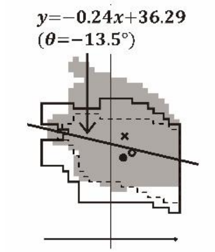
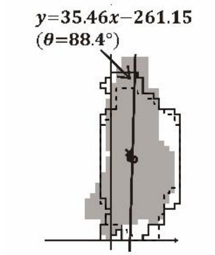
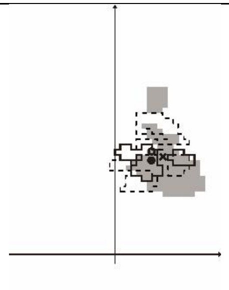
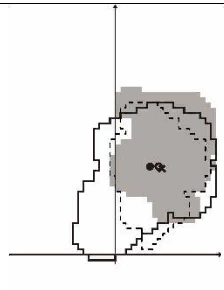
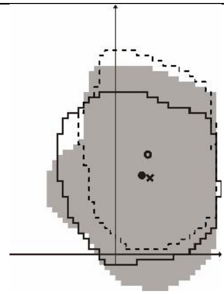
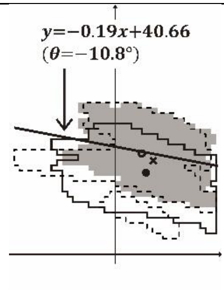
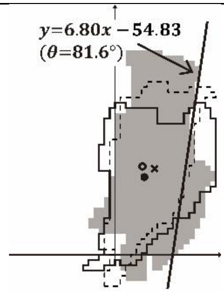
The index finger reach zone varied by interaction task. The ranges (height × width) of the index finger touch area made during T_N, T_C, T_M, T_H and T_V were 44 × 48, 64 × 66, 90 × 78, 62 × 76 and 48 × 88 mm, respectively. T_H and T_V strokes were not parallel to the horizontal or vertical axis. The slopes (95% CI) for T_H with the X-axis for P_N and P_W were −13.5° (−12.2° to −15.1°) and −10.8° (−10.7° to −12.5°), respectively. The slopes (95% CI) for T_V with the Y-axis for P_N and P_W were −1.6° (−0.7° to −2.5°) and −8.4° (−7.4° to −9.3°), respectively (with the X-axis, 88.4° and 81.6°; Table 2.3). The index finger touch areas (cm^2) were wider with P_W in all tasks, and the size of the index finger reach zone differed by hand size. The touch area during T_C was moved to the bottom left side (the 3rd quadrant; −X/−Y) as the hand size decreased. The X width was the narrowest in the H_M group and the widest in the H_S group. The touch area during T_M was the widest in the H_L group and the narrowest in the H_M group (see Table 2.3 for additional information).

Table 2.2 Classification of smartphone grasps

	Front Touch			Rear Touch	
Front View					
Rear view					
Grasp	Holding the phone with fingers and the palm (Thumb used for touch)	Supporting the bottom with the little finger (Thumb used for touch)	Holding lateral sides with fingers, the palm, and the thumb (Thumb used for touch)	Holding lateral sides with fingers and the thumb (Index finger used for touch)	Supporting the bottom with the little finger (Index finger used for touch)
Location of little finger	rear	bottom	side	side	bottom
cases (%)	33/60 (55.0)	22/60 (36.7)	5/60 (8.3)	30/30 [28/30] (96.7†)	0/30 [2/30] (3.3†)

[ ]: Data obtained in laboratory setting; †: % for pooled data (n=60)

Table 2.3 Index finger touch areas for one-handed smartphone rear interaction

		Task				
		T_N	T_C	T_M	T_H	T_V
P_N	Touch Area					
	H_S	2.2, 2.8; 1.1, 3.7; 3.6	3.8, 5.8; 0.9, 2.8; 19.4	5.0, 6.4; 0.4, 3.1; 30.2	5.0, 4.2; 0.5, 3.1; 17.3	2.8, 6.2; 0.8, 3.1; 15.5
	H_M	1.8, 3.2; 0.8, 3.7; 3.7	2.8, 4.2; 1.2, 2.9; 10.2	5.0, 6.2; 0.5, 2.9; 26.3	4.4, 3.2; 0.9, 3.3; 10.7	2.8, 5.6; 0.9, 3.1; 13.2
	H_L	1.8, 2.6; 1.0, 3.9; 2.4	3.2, 4.6; 1.1, 3.5; 12.2	5.0, 7.4; 0.3, 3.5; 37.2	4.8, 5.0; 0.5, 3.9; 17.2	3.2, 6.8; 0.8, 3.3; 14.4
	Total	2.4, 3.2; 0.9, 3.7; 5.9	4.0, 5.8; 1.0, 3.1; 20.1	5.0, 7.4; 0.4, 3.2; 37.3	5.0, 5.8; 0.6, 3.5; 21.5	3.4, 6.8; 0.8, 3.2; 17.8
P_W	Touch Area					
	H_S	2.8, 1.2; 1.4, 3.6; 1.9	5.2, 5.6; 1.4, 3.4; 22.4	6.0, 5.8; 1.0, 3.0; 32.8	6.0, 4.0; 1.2, 3.1; 17.2	4.8, 5.2; 1.2, 3.0; 19.8
	H_M	2.8, 3.0; 1.4, 3.9; 3.6	3.6, 5.4; 1.6, 3.4; 14.0	5.0, 7.4; 1.3, 3.8; 31.6	7.4, 5.0; 1.0, 3.8; 18.7	4.0, 7.6; 1.1, 3.4; 17.8
	H_L	2.8, 4.0; 1.9, 3.8; 5.4	5.2, 6.2; 1.7, 3.3; 16.1	6.2, 5.8; 1.3, 3.0; 42.0	5.6, 4.8; 1.4, 3.6; 15.5	4.6, 6.8; 1.5, 3.3; 24.9
	Total	3.4, 4.0; 1.6, 3.8; 8.0	5.2, 6.2; 1.6, 3.5; 26.1	6.4, 6.4; 1.2, 3.2; 45.0	7.4, 5.0; 1.1, 3.6; 24.7	4.8, 8.8; 1.3, 3.2; 30.4

Notes: Interactions involved five finger stroke tasks (T_N-neutral, T_C-comfortable, T_M-maximal, T_H-horizontal, and T_V-vertical), two smartphone widths (P_N-60 mm and P_W-90 mm), and three different hand-size groups (solid line, small-handed group; dotted line, medium-handed group; and grey area, large-handed group). Centers of the touch areas are indicated with filled circles for the small-handed group, unfilled circles for the medium-handed group, and crosses for the large-handed group. Numbers are the X range, Y range, center coordinates, and touch area (all in cm or cm^2)

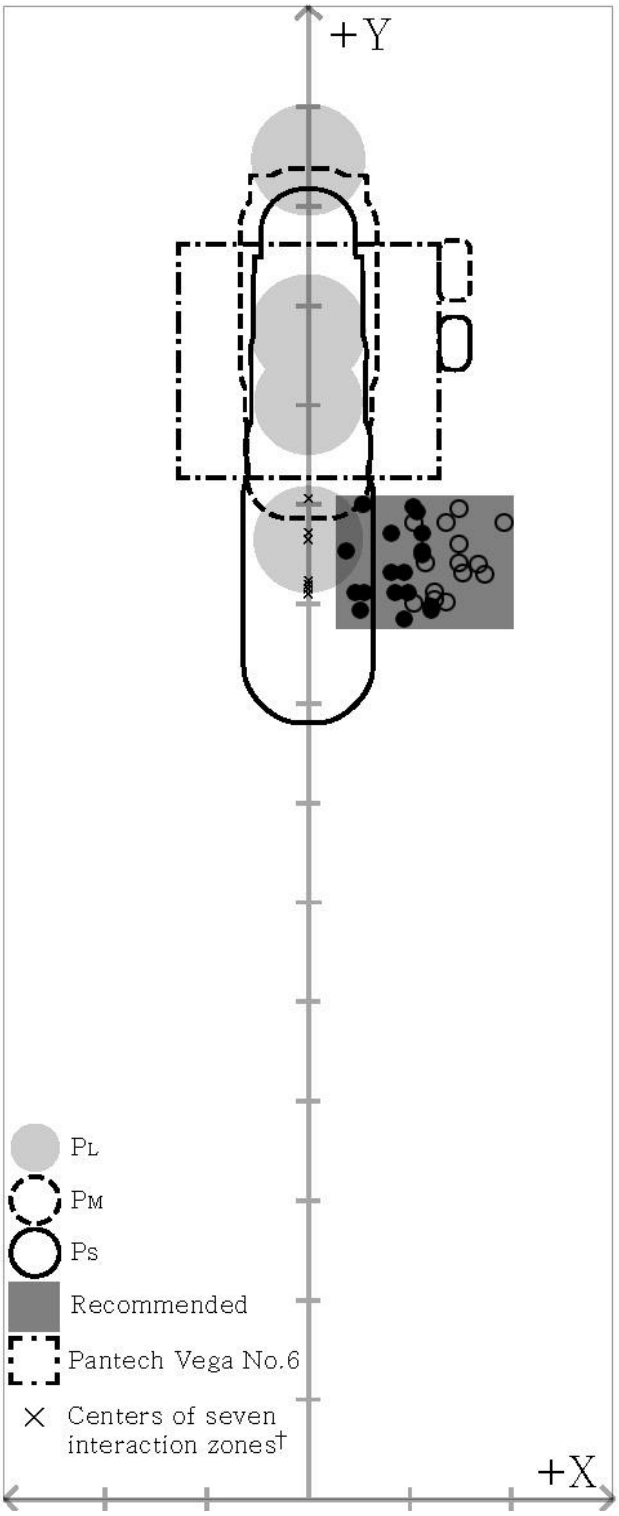


Figure 2.2 Comparison of the rear touch areas of commercial smartphones and the centers of touch areas for five tasks, two phone widths, and three hand length groups during index finger rear interaction. Total number of smartphones considered = 140 plus Pantech Vega No. 6; P_S: Small-size phone, P_M: Medium-size phone, P_L: Large-size phone; †Partially overlapped with the recommended zone (Filled circles represent the 60-mm-wide phone, and unfilled circles represent the 90-mm-wide phone; scale marker interval = 1 cm).

2.3.3. Subjective discomfort

The T, P and P × H interaction effects were significant for perceived discomfort (Table 2.4). T was divided into three groups (T_M, T_HT_V, T_CT_N), with T_M being the most uncomfortable task (58.2 vs. 39.1–14.4; Figure 2.3). P_W was more uncomfortable than P_N (40.1 vs. 27.8).

Table 2.4 Effects of task (T), phone width (P), and hand length (H) on perceived fatigue and %MVE for FDI, FDS, and ED2, which are associated with abduction, flexion, and extension of the index finger; p-values < 0.05 are underlined.

Effects	*p*-values			
	Perceived Fatigue	%MVE		
		FDI	FDS	ED2
T	<.0001	0.013	<.0001	<.0001
P	<.0001	0.0016	0.14	0.3612
H	0.17	0.45	<.0001	0.0197
T × P	0.55	<.0001	<.0001	<.0001
T × H	0.28	<.0001	<.0001	<.0001
P × H	0.03	<.0001	<.0001	<.0001
T × P × H	0.38	<.0001	<.0001	<.0001

Notes: *p*-values < 0.05 are underlined.
%MVE, percent maximal voluntary exertion; FDI-first dorsal interosseous muscle; FDS-flexor digitorum superficialis muscle; ED2-extensor digitorum 2 muscle.

2.3.4. Muscle Activation (Electromyogram)

With regard to muscle activation, four interaction effects (T × P, T × H, P × H, and T × P × H) were significant for FDI, FDS and ED2 (Table 2.4). For FDI, the effects of T and P were significant. T was divided into two groups ($T_MT_CT_VT_H$ and T_N), with T_N having the lowest muscle activation (5.2–5.4 vs. 4.2). P_N showed greater muscle activation than P_W (5.5 vs. 4.6). For FDS, the effects of T and H were significant. T was divided into three groups (T_C, $T_NT_MT_V$, T_H), with %MVE of T_C being the highest (11.5) and that of T_H being the lowest (6.0). As H-level decreased, %MVE of the FDS increased (from 5.8–7.8 to 12.2). For ED2, the effects of T and H were significant. T was divided into three groups (T_H, $T_VT_NT_C$, T_M), with %MVE of T_H being the highest (8.1 vs. 7.1–5.3). H was divided into two groups (H_S, H_MH_L), with %MVE of H_S being the highest (8.1 vs. 6.3–5.0).

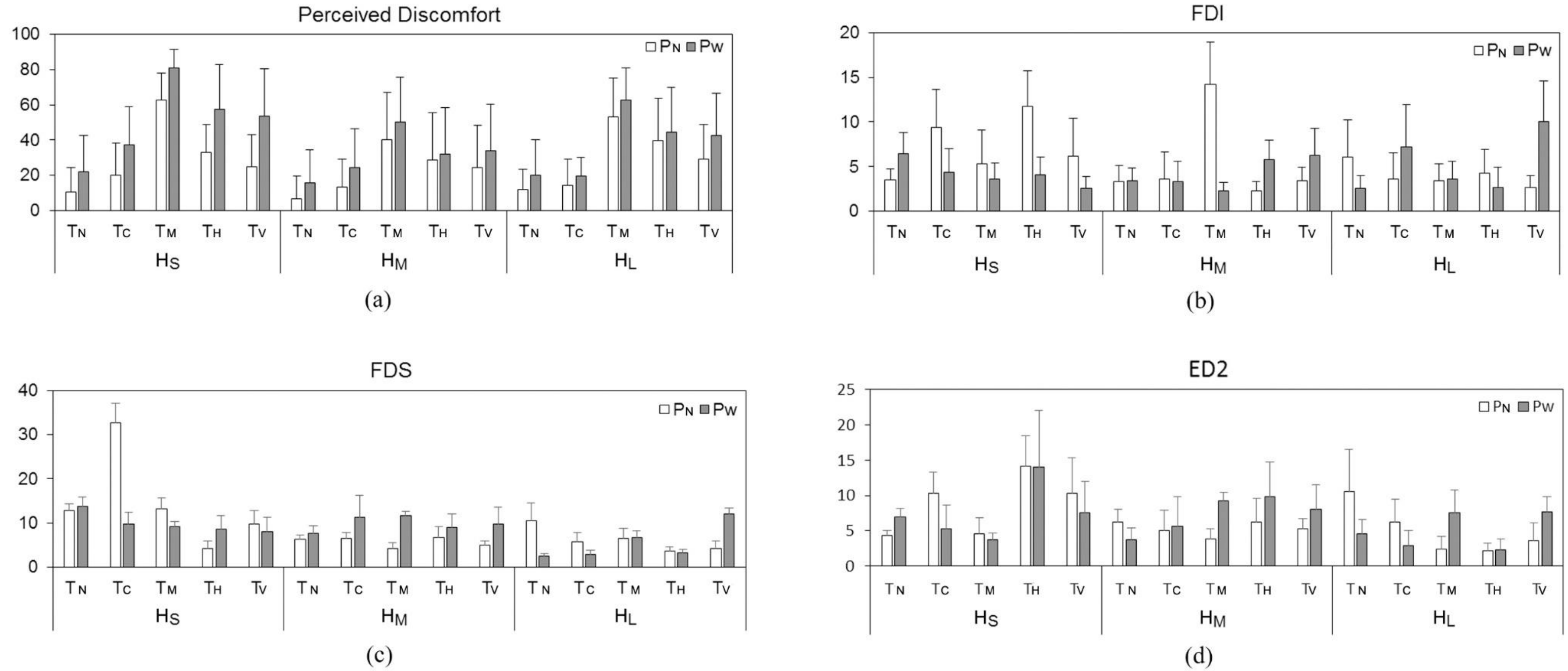


Figure 2.3 Mean (SD) perceived discomfort (PD) and muscle activation for each H and P level during five different tasks. (a) Perceived discomfort, (b) FDI = first dorsal interosseous muscle; the muscle between the thumb and the index finger, which contributes to abduction of the index finger, (c) FDS = flexor digitorum superficialis muscle; the muscle near the wrist, which contributes to flexion of the index finger, and (d) ED2 = extensor digitorum 2 muscle, the muscle positioned in the middle of the lower arm, which contributes to extension of the index finger.

Notes: P_N – phone width of 60 mm, P_W – phone width of 90 mm, T_N – neutral, T_C – comfortable, T_M – maximal, T_H – horizontal, and T_V – vertical.

2.4. Discussions

2.4.1. Grasp classification

For any given task or objective, users adopt appropriate postural strategies by considering comfort, safety, preference, accuracy and/or speed of performance (Andreoni et al. 2002; Beach et al. 2005; Kyung, Nussbaum, and Babski-Reeves 2010; Massion 1994). The current study showed that three distinct grasps were used during front interaction tasks, whereas one particular grasp (grasping two lateral sides) was dominantly used (96.7% of cases) during rear interaction. For front interaction involving the thumb, relatively stable grasps (holding the rear, lateral, and/or bottom sides of the device with the palm and fingers) were used. In contrast, for rear interaction using the index finger, some clearance between the rear surface and the index finger is required to accommodate index finger movements (flexion, extension, abduction, and adduction). To make this clearance, the lateral sides of the device need to be held tightly; the thumb and other three fingers are involved in grasping the device sides, and the palm contact area reduces (or disappears). In addition, to align the screen parallel to the eyes, users tilt their necks and/ or make radial/ulnar wrist deviations. Therefore, there is a limited degree of freedom for grasps during rear interaction. Generally, the restricted posture is deemed to cause MSDs. MSD risk factors include high task frequency, long task duration, high exertion level and restricted workspace (Punnett and Wegman 2004), all of which seem relevant to smartphone rear interaction. Further investigation is thus required to determine the MSD risk of rear interaction with respect to these factors.

2.4.2. Index finger reach zone and comparison with the rear interactions of existing smartphones

The range of the index finger reach zone (touch area) varied by task. It was affected by device size, the device's center of mass (COM), hand size, hand length and finger position on the device. During T_H, finger strokes were not parallel to the device's X-axis (i.e. slopes were made in the range from −10.8° to −13.5°). During T_V, finger strokes also showed a slope of −1.6° to −8.4° with reference to the Y-axis. Such results could have been partly due to the restricted grasp required for rear interaction, as mentioned in the discussions of *Grasp*. When determining the width and height of the rear interaction area for new smartphones, stroke behaviors observed in the current study should be taken into account.

The mean slopes made between the index finger stroke and the X-axis during T_H and T_V were larger for P_N than for P_W. As the P-level increased, index finger flexion became more important than abduction for T_H, and more index finger abduction/adduction was required for T_V. For the index finger, horizontal and vertical strokes made by abduction/ adduction appeared more difficult and less accurate than those made by flexion. Further, combined flexion/ extension and abduction/adduction were less accurate than were separate movements (flexion/extension only or abduction/adduction only), as the former requires a more delicate coordination of muscle groups. P_NT_V (mostly performed with flexion/extension) and P_WT_H (mostly performed with adduction/abduction) showed smaller slopes than did the other conditions. However, participants may not have been careful about stroke accuracy (or slope) during T_H or T_V. High stroke accuracy is not required for horizontal and vertical thumb strokes during front interaction (such as for scrolling laterally or vertically). Similarly, the slopes of horizontal and vertical strokes during rear interaction may have not been considered important by users (Woltz, Gardner, and Bell 2000). Additionally, as index finger movements during rear interaction were completely obscured by the device (i.e. there was no visual feedback regarding finger movements), movement accuracy could have been degraded further than intended.

The size of the touch area by the index finger during each task varied by H-level as well. During T_C, the reach envelope was the widest at H_S, probably because the device holding positions could be more diversified by small hands. In contrast, during T_M, the reach envelope was the widest at H_L, mostly due to longer index fingers at higher H-levels.

Rear interaction areas of 140 commercial smartphones were compared with the index finger touch locations suggested by the current study (Figure 2.2). All index finger touch centers observed in the current study were located 8.8–10.1 cm from the bottom and 0.3–2.0 cm to the right of the vertical center line (0.3–2.0 cm left for left-handed individuals). The mean (range; SD) width and height of the 140 smartphones were 74.5 (64.9–88.6; 4.5) and 148.4 (127.5–179.8; 8.4) mm. Rear interaction zones of the 135 models were located on the vertical centerline (Y-axis), and those of five Samsung Galaxy phones (S6TM, S6 Edge™, S6 Edge Plus™, S7™, and Edge™) were located 13–16 mm right to the Y-axis. The Y coordinate range of rear interaction zones of all models was 78–140 mm. The mean (SD) X and Y coordinate values of the center points of rear interaction zones were 0.5 (2.7) and 111.6 (6.6).

Three phone groups, small-size phone (P_S), medium-size phone (P_M), and large-size phone (P_L) were determined by applying the K-Means clustering method to the 140 models' width and height data (Figure 2.2). The mean (SD) width and height of each group were 70.4 (1.9) × 141.0 (4.9) for P_S, 76.9 (2.4) × 152.7 (3.9) for P_M, and 87.3 (2.0) × 173.0 (5.2) for P_L, respectively. The range of the X and Y coordinate values of the rear interaction zones for each group were -6–16, 78–132 (P_S), -7–16, 99–134 (P_M), and -6–6, 91–140 (P_L), respectively. The mean (SD) ED for each group was 18.4 (4.3) for P_S, 22.7 (3.7) for P_M, and 24.7 (12.8) for P_L. The effect of phone group on the location of rear interaction zones was significant ($p < 0.0001$), with the initial three phone groups being grouped into two (P_S and P_MP_L).

Except for the five Samsung models, rear interaction zones were symmetrical around the vertical centerline. It is mostly due to consideration of both handedness and symmetric design. The W×H interaction effect and the means of three clusters indicated that interaction zones of larger smartphones were located higher (see Figure 2.2). Only seven out of 140 (5%) smartphones provided rear interaction zones partially overlapped with the recommended zone. Six of them belonged to P_S (LG Volt™, LG G2 Mini™, LG Tribute2™, LG LFino™, LG Leon™, and LG G2 Lite™), and one (Lenovo Phab2 Pro™) belonged to P_L. The center of the rear interaction of LG Tribute 2™ (0, 93) was the nearest to the center of recommended zone.

During smartphone rear interactions, the device is typically held with four digits, while the index finger touches the rear interaction zone. The rear interaction zones provided by the current smartphone models are on average 21mm higher than recommended. As the location of the rear interaction zone gets higher, abduction of the index finger increases. Such a condition can lead to high hand discomfort. Therefore, it is necessary to determine the rear interaction zones more carefully in the case of future smartphone models.

2.4.3. Subjective discomfort

Subjective discomfort varied by task (Table 2.4), mostly due to differences in the direction and range of index finger movements required for each task. Among these tasks, T_M was the most uncomfortable (58.2 vs. 39.1). Participants also reported higher discomfort ratings after using P_W than after using P_N (40.1 vs. 27.8), which is likely due to the decreased degree of freedom of grasp with increased device width. The P × H interaction effect was also significant. After using P_W, the H_S group reported higher discomfort ratings than did the other two groups (50.24 vs. 38.85) and also reported discomfort ratings in the range from 10.2 (T_N) to 62.8 (T_M) for P_N vs. from 22.1(T_N) to 81.0 (T_M) for P_W. If rear interaction is made on a 90-mm wide smartphone, the expected level of discomfort for the small-hand group (hand size < 169.9 mm) is 50.2, while that for the other groups will be in the range from 31.2 to 38.9.

Grip strength changes with grip span. Maximum muscular strength generally occurs in a neutral posture, which may help prevent MSD. Ruiz et al. (2006) showed that the optimal grip span was between 14% (for men) and 25% (for women) of the hand span (the tip of the first digit to the tip of the fifth digit). Chengalur, Rodgers, and Bernard (2004) showed that the optimal grip span changed with grip method (4.5–9.5 cm for power grip and 2.5–7.5 cm for pinch grip). Based on these findings, the phone width recommended for one-handed smartphone use is ~7.5 cm, which provides certain levels of power and precision. In addition, tactile sensitivity over the glabrous skin of the human hand increases distally (the highest sensitivity is at the fingertips), which is primarily due to increased mechanoreceptors in the fingertips (Johansson and Vallbo 1979). Therefore, it is expected that grasp discomfort will increase if fingertips contact lateral edges of devices that are sharp and not properly rounded.

2.4.4. Muscle Activation (Electromyogram)

For %MVE of FDI, involved in index finger abduction, the T effect was significant. %MVE of FDI was the highest during T_C. For %MVE of FDI, the P effect was also significant. Smartphone width affected FDI muscle activation, although the difference was small (P_N = 5.5%, P_W = 4.6%). The post hoc analysis of the T × P × H interaction effect showed that the highest (14.2) %MVE for FDI was in the $T_M P_N H_M$ condition, the second highest (11.7) was in the $T_H P_N H_S$ condition and the lowest (4.1) was in the $T_H P_W H_S$ condition. As noted in section 3.2, when small-handed individuals make horizontal strokes on a narrower device, more abductions of the index finger occurred, whereas more flexions occurred for a wider device. Indeed, %MVE for FDS, which involves index finger flexion, increased from 4.3 for $T_H P_N H_S$ to 8.6 for $T_H P_W H_S$.

Post hoc analyses of the T effect and T × P × H interaction effects on FDS showed that T_C required the highest %MVE (11.5) among the five tasks, and the $T_C P_N H_S$ combination required the greatest activation (32.6) among all treatments. Based on these results, small-handed individuals appeared to exert high muscular efforts, even during comfortable strokes. The post hoc analysis of the H effect exhibited greater FDS activation with smaller hands (%MVE of $H_S/H_M/H_L$ = 15.5/9.0/6.3), which can be accounted for by a wider finger ROM required for smaller hands (hence, shorter fingers) to make strokes of the same length.

%MVE of the ED2, pertinent to index finger extension, was significantly higher for T_H, primarily because extension of the index finger, as well as abduction and adduction were needed to make horizontal strokes in a restricted grasp. %MVE of the ED2 was, however, not much higher for T_V compared to that for other tasks. T_V required only narrow ranges of index finger flexion and extension (primarily involving interphalangeal joint movements), but not wider ranges of flexion and extension (involving interphalangeal and metacarpophalangeal joint movements). Low %MVE for the ED2 indicated that vertical strokes were not difficult, although small-handed individuals still showed relatively higher values (9.0 vs. 6.0–5.7).

Overall, the maximum %MVE of the index finger observed in the current study was 32.6 (%MVE of the FDS in the $T_C H_S$ condition), and the other cases required muscle activation <20% MVE. It can be concluded that the five grasps considered in the current study were not highly physically demanding. The current study, however, considered only short-term finger strokes, and did not examine the conditions of longer duration and high repetition that can exacerbate local muscle fatigue. These factors should be accounted for to determine the level of MSD risks involved in rear interaction. Indeed, loads as low as 4–6% MVC can cause fatigue (Chaffin, Andersson, and Martin 2006).

One-handed rear interaction using the index finger can provide some benefits. First, the degree of design freedom increases since some functions and features on the front can be moved to the rear, which in turn helps increase the front screen size. Second, fingers no longer obscure the front screen during finger interaction. Third, instead of being used for touch interaction, the thumb contributes to a firmer grasp and easier horizontal strokes (Wobbrock, Myers, and Aung 2008).

2.4.5. Limitations

There are some limitations in the current study. First, as only Korean individuals in their 20s participated, characteristics of other ethnic and age groups are unknown. For ethnic groups with larger hands, the maximum reach zones will increase, and for those with shorter hands, the size of index finger reach zones will likely reduce and touch centres likely become lower. For example, the mean (SD) hand length of Americans is 18.7 (1.03) cm (Chengalur, Rodgers, and Bernard 2004) vs. 17.6 (1.99) cm for Koreans (SizeKorea 2010). Age-related differences are also expected. In the case of Korean teenagers, the mean (SD) hand length is 16.9 (1.57) cm; thus, index finger reach zones of this group are expected to be narrower and located in a lower region than were those observed in the current study. Joint ROMs reduce with age (Stubbs, Fernandez, and Glenn

1993). Therefore, index finger reach zones of the older population are likely similar to those of teenagers. For the universal design of smartphone rear interaction, such differences should be taken into account. Second, various hand sizes may have not been reflected in the results of the field study, as it used a random approaching method, and hand size was not evaluated. Third, the ratios of men to women in three hand groups were not well balanced (no, one, and all women for the large, medium, and small hand groups, respectively). As hand function strengths are relatively low for women (23 ± 7 kg vs. 40 ± 9 kg in grasp strength [Chao 1989]), female participants may have felt more uncomfortable with the same device and task than the male participants did. Fourth, changes in the device weight and COM due to the smartphone housings could have affected experimental results. Though the housings were developed to control the size and weight of the two experimental smartphones, the height and weight of the experimental phones were changed compared to the original phones. COMs of the experimental devices were also different from the original COMs, as epoxy is a very light material. These changes could have affected grasp and EMG results, though not substantially. Fifth, reach zones can change with finger input methods. Different touch pressure and finger movements are required for using touch screens and physical buttons, potentially resulting in slightly different finger postures and grasps. Sixth, grasp and grasp comfort can be affected by the sharpness of lateral and bottom edges. The housings used in the current study were rounded with a 1-mm radius for the lateral edges and a 10-mm radius for the bottom corner edges, while actual edge designs vary by smartphone. Seventh, some finger touches were made outside of the touch screen (in the case of T_M and T_H, parts of the left, right, or bottom touch areas were partially truncated). Eighth, the current study considered the ‘sitting without desk’ condition (30 people in the field study) and the ‘sitting at desk’ condition (30 people in the laboratory study), but did not consider other conditions (such as walking). Ninth, in the field study, the grasps during rear interaction were observed when scrolling up the screen three times (similar to T_V), but grasps during other tasks were not considered. Tenth, although index finger flexion, extension, adduction and abduction were analyzed from the perspective of MSD risk, index finger joint angles, wrist movements (flexion, extension, and ulnar/radial deviation), prolonged task and high task repetition were not considered. Eleventh, 60mm- and 90mm-width (the range of width of existing smartphone models) were used as the levels of device width because there was no study for the smartphone dimensions. Future study is needed to investigate the proper smartphone dimensions as the fundamental study about smartphone.

2.5. Conclusions

This study investigated the effects of interaction task type, device width and hand length on smartphone grasp, index finger reach zone, subjective discomfort and muscle activation related to smartphone rear interaction using the index finger. We found that a single grasp method (holding lateral sides with fingers and the thumb) was predominantly used during rear interaction. Finger reach zones varied by task, device width and hand size. Horizontal and vertical strokes were neither parallel nor orthogonal to the device. Discomfort increased with the 90-mm-wide device, and the FDI was highly activated with the 60-mm-wide device. The small-handed group showed higher FDS activation, indicating more index finger flexion. Rear interaction regions of five commercialized smartphones should be lowered 20 to 30 mm for more comfortable interaction. These fundamental findings will contribute to the ergonomic design of rear-interactive smartphones.

Chapter 3. [Study 2] Non-flexible Smartphones: Smartphone Dimensions Considering Grip Comfort and Attractive Design

3.1. Introduction[2]

The size of a smartphone design affects both its grip comfort and attractiveness. Increasing smartphone and display sizes can degrade the grip comfort and portability of the device (Chowdhury & Kanetkar, 2017): Models with 3–4” (76–102 mm) screens allow one-hand interaction, whereas widescreen phablet (phone + tablet) phones sometimes require two hands for use. Operating large-screen mobile phones with one hand increases the risk of dropping the device because of grip insecurity (Chiang, Wen, Chen, & Hou, 2013). Additionally, the physical form or design of a product can induce positive aesthetic impressions of design attractiveness, elegance, and beauty (Crilly, Moultrie, & Clarkson, 2004) and influence purchase decisions (Chrisprastika, 2015). As such, both grip comfort and design attractiveness should be considered when determining smartphone sizes.

No existing grip studies have cohesively investigated the four major dimensions (height, width, thickness, and edge roundness) of a rectangular parallelepiped. Some previous studies researched cylindrical objects whose major dimension was their diameter (e.g., Grant, Habes, & Steward, 1992; Kong & Lowe, 2005; Lee & Zhang, 2005; Seo & Armstrong, 2008), whereas others manipulated only one dimension of an object, such as width, and controlled the others, such as thickness and height (e.g., Blackwell, Kornatz, & Heath, 1999; Espana-Romero et al., 2008; Lee, Kong, Lowe, & Song, 2009; Lee, Kyung, Lee, Moon, & Park, 2016; Ruiz-Ruiz, Mesa, Gutierrez, & Castillo, 2002; Shivers, Mirka, & Kaber, 2002). Chowdhury and Kanetkar (2017) used seven smartphone models and concluded that 138H × 70W × 8T was the most preferred size considering smartphone width and volume. These two dimensions were, however, not manipulated, and smartphone weight was not controlled, which could have confounded their result. In the case of a rectangular parallelepiped such as a smartphone whose overall form is determined by height, width, thickness, and edge roundness, more than one dimension can affect the gripping posture, and interactive effects may exist between dimensions. Dimensions should thus be considered in conjunction to thoroughly evaluate smartphone grip comfort.

Even for objects of the same shape, grip comfort varies with size. This relationship can be partially explained by the fact that the tactile sensitivity of the hand (in terms such as pressure and vibration) changes across its skin. The distal part of the hand is more sensitive to pressure and vibrations

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[2] This chapter was published as a journal paper.
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because the density of mechanoreceptive units decreases from the fingertip to the remaining finger to the palm (Vallbo & Johansson, 1984). A two-point discrimination study performed by Vallbo and Johansson (1984) found the mean two-point threshold at the tip of the index finger was 1.6 mm, five times less than the value determined for the palm, indicating the palm is less sensitive. Louis et al. (1984) found the mean value for stationary two-point discrimination in the little finger was 3.3 mm, significantly larger than the value for the index finger (although no exact value was reported for this). As these findings suggest, the just-noticeable difference varies between different parts of the hand and different tasks. Changing object dimensions can thus lead to changes in overall grip comfort, as the areas of contact between the hand and object vary with grip.

Hand size should also be considered when determining the proper size for hand-held devices in terms of grip comfort, strength, and preference. Kong and Lowe (2005) showed that perceived handle grip comfort was maximized at diameters (circumferences) of 37–44 (116–138) mm and 41–48 (129–151) mm for females and males, respectively. Lee et al. (2016) investigated grip comfort and postures, index finger reach areas, and muscle activations associated with different hand sizes, device widths, and tasks during index finger interactions on the rear areas of smartphone mock-ups. A greater width (90 mm) increased perceived grip discomfort overall; however, phones 60 mm wide were found to increase the muscle activation of the first dorsal interosseous for users with shorter hand lengths by a factor of approximately three relative to the 90 mm width, increasing the perceived discomfort by 12.3%. The necessity of accounting for hand size when determining smartphone size has, thus, been demonstrated.

Grip comfort during voice calls is critical for the overall smartphone grip comfort. A typical grip adopted during voice calls involves contact between the distal parts of the hand and side surfaces and/or edges: The thumb firmly contacts the lateral side and edges of the device while all or most of the remaining fingers or fingertips firmly contact the opposing lateral side and edges. As reviewed above, distal portions of the hand are more sensitive to pressure than proximal portions (Johansson & Vallbo, 1979, 1983), and the relatively high forces enacted on the narrow lateral sides and edges of the phone in this grip elevate the contact pressure on pressure-sensitive finger patches. In contrast, no firm grip is required for other smartphone tasks involving touchscreen interactions such as one- or two-thumb smartphone touch interactions. During these activities, the device lies loosely on the palm and the fingers instead, in rare cases receiving additional support from the little finger on the bottom or rear of the device (Lee et al., 2016). As touch interaction tasks do not require firm grips, grip comfort is less sensitive to the device form during these tasks relative to voice calls or hand-carrying tasks. Indeed, Yi, Park, Im, Jeon, & Kyung, (2017) demonstrated the variations in grip comfort between smartphones of different forms were more significant during voice calls than any other smartphone task (i.e., texting, watching videos, or viewing images), and the narrow lateral sides due to edge curvatures led to poor grip comfort during voice calls. Voice calling remains one of the most common smartphone tasks in South Korea (KISDI, 2014, 2015, 2017) and the United States (Fluent LLC, 2016; Gilbert, 2012; Hakernoon, 2017; Smith, 2015).

The objectives of this study were twofold: first, to investigate the effects of hand length, major dimensions (height, width, thickness, and edge roundness), and mass on the one-handed grip comfort and attractiveness of smartphone designs, and second, to recommend corresponding smartphone dimensions and masses based on these results that can provide high grip comfort and design attractiveness. Grip during voice calls was given particular focus as it requires firmness rather than precision and involves the more sensitive distal parts of the hand. Three hypotheses were developed: Some dimensions influence overall smartphone grip comfort more strongly than others (hypothesis 1; H1), there exist interactive effects between smartphone dimensions (H2), and there is a suitable mass associated with a given smartphone size (H3).

3.2. Material and Methods

A three-stage study was conducted to determine the ranges of smartphone dimensions (height, width, thickness, and edge roundness) and mass associated with high grip comfort and design attractiveness. All three stages involved three hand-length groups. Stage I addressed H1 by determining the range of each dimension suitable for grip comfort and the relative strengths of their influences. Stage II addressed H2 by examining the main and interaction effects on grip comfort and design attractiveness of the influential dimensions identified in Stage I. Stage III addressed H3 by varying the masses of smartphone mock-ups fabricated using the dimensions identified in Stages I and II.

3.2.1. Participants

Thirty-six individuals (18 males and 18 females) participated in Stage I, with a mean age of 22.3 years and standard deviation (SD) of 3.4 years. A separate set of 36 individuals (14 males; 22

females) with a mean age of 22.7 years (SD = 3.2 years) participated in Stages II and III. All participants were recruited from a university population and had at least three years of smartphone use experience. All were right-handed and healthy without any musculoskeletal diseases affecting the wrist. Efforts were made to recruit individuals with a wide range of hand lengths (Table 3.1). All participants provided informed consent and were compensated for their time. The experimental protocol was approved by a local institutional review board.

Table 3.1 Participant groups and hand lengths

	Stage	Short hand (≤165.6 mm†)	Medium hand (173.6–178.6 mm†)	Large hand (≥186.6 mm†)	Total
Number of participants (male:female)	I	12 (0:12)	12 (6:6)	12 (12:0)	36 (18:18)
	II and III	12 (1:12)	12 (2:10)	12 (12:0)	36 (14:22)

†165.6 mm, 173.6 mm, 178.6 mm, and 186.6 mm correspond to 30th, 45th, 55th, and 70th percentiles, respectively, according to SizeKorea (2004).

3.2.2. Experimental design

Hand length ($HL_{S/M/L}$; a between-subjects factor) was considered an independent variable and divided into three levels: HL_S (short hand length; ≤165.6 mm, 30^{th} percentile), HL_M (medium hand length; 173.6–178.6 mm, 45^{th}–55^{th} percentile), and HL_L (large hand length; ≥186.6 mm, 70^{th} percentile). The stated percentile values represent the hand lengths of persons 20–50 years old in the South Korean population (SizeKorea, 2004). These specific percentiles were selected to ensure a minimum difference of 5 mm in hand length between groups.

Stage I consisted of four sessions conducted to determine the ranges of four smartphone dimensions—height (P_{HT}), width (P_{WD}), thickness (P_{TH}), and edge roundness (P_{RN})—suitable for grip comfort and the relative strengths of their influence. In each session, one of the four dimensions was varied whereas the other three dimensions were fixed at the rounded mean values (P_{HT} = 140 mm, P_{WD} = 70 mm, and P_{TH} = 8 mm) of 52 smartphone models released in South Korea between 2013 and 2015 (P_{HT} = 144.1 mm, P_{WD} = 73.2 mm, and P_{TH} = 8.4 mm), and the P_{RN} was fixed at 2 mm (the midrange value of the 0–4 mm edge radius range feasible for the mean P_{TH}). This allowed the exploration of much wider ranges for the four dimensions than would have been possible otherwise. The grip comfort suitability of the manipulated dimensions was assessed. Based on the mean values of 52 smartphone models, 29 P_{HT} levels (110–180 mm, 2.5 mm

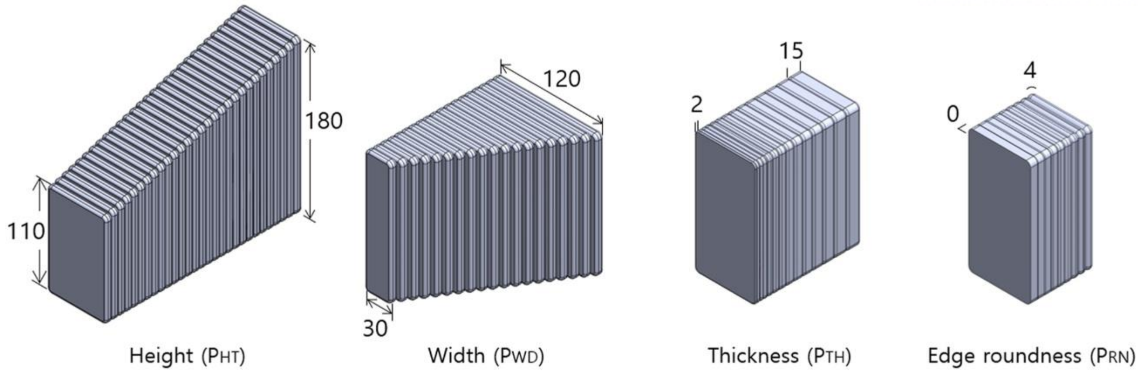


Figure 3.1 Mock-ups used in Stage I. 29 P_{HT} levels (110–180 mm, 2.5 mm intervals), 19 P_{WD} levels (30–120 mm, 5 mm intervals), 14 P_{TH} levels (2–15 mm, 1 mm intervals), and 9 P_{RN} levels (0–4 mm, 0.5 mm intervals). One of the four dimensions was varied, whereas the other three dimensions were fixed (P_{HT} = 140 mm, P_{WD} = 70 mm, P_{TH} = 8 mm, and P_{RN} = 2 mm).

intervals), 19 P_{WD} levels (30–120 mm, 5 mm intervals), 14 P_{TH} levels (2–15 mm, 1 mm intervals), and 9 P_{RN} levels (0–4 mm, 0.5 mm intervals) were considered in each session (see Figure 3.1). The P_{HT} session thus had a 3 (HL) × 29 (P_{HT}; within-subjects) mixed factorial design, the P_{WD} session a 3 (HL) × 19 (P_{WD}; within-subjects) mixed factorial design, the P_{TH} session a 3 (HL) × 14 (P_{TH}; within-subjects) mixed factorial design, and the P_{RN} session a 3 (HL) × 9 (P_{RN}; within-subjects) mixed factorial design. The session orders of presentation and factor levels were randomized.

Stage II identified the design dimension combination that corresponded to high grip comfort and attractiveness by considering the main and interaction effects of P_{WD} and P_{TH}, the dimensions with the strongest grip comfort influence from Stage I. The bivariate correlations between three types of grip comfort (grip comfort considering only phone width, grip comfort considering only phone thickness, and grip comfort considering overall dimensions) and between each type of grip comfort and design attractiveness were also examined. The values determined in Stage I were used for P_{HT} and P_{RN}, (P_{HT} = 140 mm and P_{RN} = 2.5 mm). The two values determined for P_{WD} in Stage I (65/70 mm) and 60 mm were used for P_{WD} (P_{WD}-S/P_{WD}-M/P_{WD}-L = 60/65/70 mm). The value determined for P_{TH} in Stage I (P_{TH} = 8 mm) was used as a median level for P_{TH} ($P_{TH\text{-}S}$/$P_{TH\text{-}M}$/$P_{TH\text{-}L}$ = 7/8/9 mm), resulting in a 3 (HL) × 3 (P_{WD}; within-subjects) × 3 (P_{TH}; within-subjects) mixed factorial design. The effect of mass on grip comfort was minimized in Stages I and II by mounting a bar shaped epoxy smartphone mock-up on a smartphone holder (OMT, South Korea;

Figure 3.2 Smartphone mock-up mounted on a holder used in Stages I and II to minimize the effect of mass on grip comfort. (Holder clip could be moved freely to adjust mock-up angle, and the bottom was attached to the desk via suction.)

see Figure 3.2), to reduce the size–weight illusion (Charpentier, 1891: larger objects are perceived to be lighter than smaller objects, even if they are equal in mass). The mock-up orientation and height varied freely. Each participant grasped the mounted smartphone using a grip posture required during voice calls for 10 s with their right hand while seated on a fixed-height chair. Previous studies on grip force and comfort have considered task durations ranging from 3 s to 10 min (Dianat, Nedaei, & Nezami, 2015; Dong et al., 2007; Edgren, Radwin, & Irwin, 2004; Grant et al., 1992; Harih & Dolšak, 2013; Hur, Motawar, & Seo, 2012; Husain, Khan, & Hasan, 2013; Kong & Lowe, 2005; McGorry, 2001).

Stage III examined the effect of mass on grip comfort (GC_{MS}) by varying the masses of mockups fabricated using the dimensions determined in Stages I and II (P_{HT} = 140 mm, P_{WD} = 65 mm, P_{TH} = 8 mm, and P_{RN} = 2.5 mm). Considering a mass just-noticeable difference of 7%–10% (Allen & Kleppner, 1992; Jones & Lederman, 2006), seven levels of phone mass (P_{MS}; a within-subjects factor) were defined from 106–198 g (the 1.5th and 98.5th percentiles, respectively) at 10% mean mass intervals, with the mean mass of the 52 sampled smartphone models (152 g) as the median level. Every participant used his/her right hand to grasp each of seven mock-ups placed on a desk without a holder and assumed a phone call grip posture for 10 s. There was a 5-min break time before the second repetition of each stage and between Stages II and III.

3.2.3. Data collection and processing

Participants evaluated the grip comfort suitability of each dimension on a seven-point scale (e.g., for width 1: much too narrow, 2: too narrow, 3: a bit too narrow, 4: suitably wide, 5: a bit too wide, 6: too wide, and 7: much too wide) in Stage I. In Stage II, each participant responded to four questions on a seven-point scale regarding: (1) grip comfort based exclusively on phone width (GC_{WD}), (2) grip comfort based exclusively on phone thickness (GC_{TH}), (3) overall grip comfort (GC_{OV}), and (4) phone design attractiveness based exclusively on phone size (PD_{AT}). The descriptors for the first three questions were (1) very uncomfortable, (2) uncomfortable, (3) somewhat uncomfortable, (4) neutral, (5) somewhat comfortable, (6) comfortable, and (7) very comfortable, whereas those for phone design attractiveness were (1) very unattractive, (2) unattractive, (3) somewhat unattractive, (4) neutral, (5) somewhat attractive, (6) attractive, and (7) very attractive. In Stage III, participants evaluated grip comfort on a seven-point scale similar to that described for Stage II but based exclusively on the mass (GC_{MS}). The elapsed times for Stages I, II, and III were 60, 40, and 20 min, respectively.

3.2.4. Data analysis

All data from both repetitions were used in the analysis. For the grip comfort data obtained in Stage I, a two-way mixed factor analysis of variance (ANOVA) (hand length and each dimension) was conducted. Further, the ratio of the suitable grip comfort range to the entire explored range was calculated for each dimension. A three-way mixed factor ANOVA (hand length, phone width, and phone thickness) was conducted for each of the three grip comfort data types (GC_{WD}, GC_{TH}, and GC_{OV}) and the design attractiveness (PD_{AT}) data obtained in Stage II. The bivariate associations between the four dependent measures

(GC_{WD}, GC_{TH}, GC_{OV}, and PD_{AT}) were also analyzed using the Pearson correlation coefficient. A two-way mixed factor ANOVA (hand length and phone mass) was conducted for the grip comfort data (GC_{MS}) obtained in Stage III. When the ANOVA results showed significant main or interaction effects, post hoc pairwise comparisons were performed using Tukey's honestly significant difference (HSD) test. An additional comparison was performed between 52 smartphone models released in South Korea and 286 models released worldwide from 2013–2015 in terms of their mean and interquartile values to examine whether smartphone models for these two markets were different in size, and hence indirectly examine whether the results of this study could be generalized to other ethnic groups (note: this study considered only the young South

Korean population). Additionally, the smartphone dimensions determined in this study were compared with the mean and quartile values of these two markets. All statistical analyses described above were performed using JMP™ (v11, SAS Institute Inc., Cary, NC), with significance defined as $p < .05$.

3.3. Results

This section describes the ANOVA and post hoc test results from data obtained in each stage as well as the dependent variable correlations. The effect of HL was found to be nonsignificant ($p \geq .11$; Tables 3.2 and 3.3) for all dependent variables (i.e., the grip comfort and phone design attractiveness variables).

Table 3.2 Effects of hand length and each smartphone dimension on grip comfort dimension suitability.

Phone dimension manipulated	Independent variables	p-values	F ratio	Partial η2	Best dimension (suitable dimension range for grip comfort (mm); range ratios)
Height only	HL	0.78	$F_{2, 33}$ = 0.25	0.015	-
	P_{HT}	<0.001*	$F_{28, 924}$ = 126.77	0.793	140 (130.0–150.0†; 28.6%‡)
	HL × P_{HT}	0.11	$F_{56, 924}$ = 1.24	0.070	
Width only	HL	0.19	$F_{2, 33}$ = 1.90	0.103	-
	P_{WD}	<0.001*	$F_{18, 594}$ = 450.08	0.932	70 (65–75†; 11.1%‡)
	HL × P_{WD}	0.85	$F_{36, 594}$ = 0.64	0.037	
Thickness only	HL	0.63	$F_{2, 33}$ = 0.47	0.028	-
	P_{TH}	<0.001*	$F_{13, 429}$ = 273.49	0.892	8 (7–9†; 15.4%‡)
	HL × P_{TH}	0.42	$F_{26, 429}$ = 1.032	0.059	
Edge roundness only	HL	0.74	$F_{2, 33}$ = 0.30	0.018	-
	P_{RN}	<0.001*	$F_{8, 264}$ = 168.71	0.836	2.5 (1.5–2.5†; 25.0%‡)
	HL × P_{RN}	0.09	$F_{16, 264}$ = 1.52	0.084	

HL = hand length, P_{HT} = phone height, P_{WD} = phone width, P_{TH} = phone thickness, and P_{RN} = phone edge roundness.

*p values below 0.05

†Range of dimensions in group A according to Tukey's HSD test

‡Ratio of range suitable for grip comfort to entire explored range

3.3.1. Determining the range of each smartphone dimension suitable for grip comfort (Stage I)

Table 3.2 shows the effects of hand length and each smartphone dimension on dimensional suitability for grip comfort. During single-dimension manipulation, P_{HT}, P_{WD}, P_{TH}, and P_{RN} significantly affected grip comfort dimension suitability ($p < .0001$). P_{HT} level 13 (140 mm) scored closest to the “suitable” device height of 4 (at 3.96), and ten levels (levels 8–18; 130.0–150.0 mm) belonged to the same group as level 13. P_{WD} level 9 (70 mm) scored closest to 4 (at 4.17), and three levels (levels 8–10; 65–75 mm) belonged to the same group. P_{TH} level 7 (8 mm) scored closest to 4 (at 4.00), and three levels (levels 6–8; 7–9 mm) belonged to the same group. P_{RN} level 6 (R = 2.5 mm) scored closest to 4 (at 3.97), and three levels (levels 4–6; 1.5–2.5 mm) belonged to the same group. The low suitable-to-overall-range ratios (11.1%–28.6%) shown in Table 3.2 indicate only narrow dimensional ranges provide grip comfort. P_{WD} and P_{TH}, with significantly narrower ratios (11.1% and 15.4%), appeared to influence grip comfort more strongly than other dimensions, supporting H1.

3.3.2. Device width and thickness, and their interaction effect on three types of grip comfort (Stage II)

Table 3.3 shows the results of hand length, device width, and device thickness effects on grip comfort. When phone widths and thicknesses were manipulated simultaneously, the HL × P_{WD} interaction effect on GC_{WD} was significant ($p = .044$). Post hoc analysis results showed six additional treatments belonged to group A alongside the HL_S-65 mm condition, which exhibited the highest mean (SD) GC_{WD} of 5.3 (1.1). The HL_M and HL_L groups judged the 60 mm-wide mock-up to produce poor grip comfort, with HL_M-60 mm in group B and HL_L60 mm in group C (the worst). The effect of P_{WD} on GC_{WD} was also significant ($p = .0002$), and post hoc analysis results showed only one width (70 mm) belonged to group A with the 65-mm width, which had the highest mean (SD) GC_{WD} at 4.9 (1.2). Although HL × P_{WD}, HL × P_{TH}, and P_{WD} × P_{TH} interactions all significantly influenced GC_{TH} ($p \leq .047$), post hoc analyses indicated that all the treatments belonged to the same group.

Table 3.3 Main and interaction effects of hand length (*HL*), phone width (P_{WD}), and phone thickness (P_{TH}) on three types of grip comfort [GC_{WD} (considering only phone width), GC_{TH} (considering only phone thickness), and GC_{OV} (considering overall dimensions)] and phone design attractiveness (PD_{AT})

		HL	P_{WD}	P_{TH}	HL × P_{WD}	HL × P_{TH}	P_{WD} × P_{TH}	HL × P_{WD} × P_{TH}
GC_{WD}	p-value	0.55	<0.001*	0.62	0.044*	0.78	0.10	0.31
	F-ratio	$F_{2, 44}$ = 0.614	$F_{2, 66}$ = 10.074	$F_{2, 66}$ = 0.480	$F_{4, 66}$ = 2.594	$F_{4, 66}$ = 0.436	$F_{4, 132}$ = 2.063	$F_{8, 132}$ = 1.243
	partial η2	0.027	0.234	0.014	0.136	0.026	0.059	0.070
GC_{TH}	p-value	0.31	0.19	0.093	0.047*	0.009*	0.026*	0.92
	F-ratio	$F_{2, 44}$ = 1.222	$F_{2, 66}$ = 1.728	$F_{2, 66}$ = 2.466	$F_{4, 66}$ = 2.557	$F_{4, 66}$ = 3.670	$F_{4, 132}$ = 2.886	$F_{8, 132}$ = 0.407
	partial η2	0.069	0.050	0.070	0.134	0.182	0.080	0.024
GC_{OV}	p-value	0.20	0.003*	0.13	0.028*	0.001*	0.20	0.83
	F-ratio	$F_{2, 44}$ = 1.711	$F_{2, 66}$ = 6.313	$F_{2, 66}$ = 2.103	$F_{4, 66}$ = 2.913	$F_{4, 66}$ = 5.105	$F_{4, 132}$ = 1.330	$F_{8, 132}$ = 0.471
	partial η2	0.094	0.161	0.060	0.150	0.236	0.039	0.028
PD_{AT}	p-value	0.20	<0.001*	0.66	0.17	0.069	0.39	0.066
	F-ratio	$F_{2, 44}$ = 1.681	$F_{2, 66}$ = 14.105	$F_{2, 66}$ = 0.429	$F_{4, 66}$ = 1.656	$F_{4, 66}$ = 2.338	$F_{4, 132}$ = 0.886	$F_{8, 132}$ = 1.546
	partial η2	0.092	0.299	0.013	0.091	0.124	0.026	0.086

*p values below 0.05

The HL × P_{WD} interaction significantly influenced GC_{OV} (p = .028). Six other treatments belonged to group A with HL_S-65 mm, which had the highest mean (SD) GC_{OV} of 5.2 (1.0). The 60 mm-wide mock-up was evaluated poorly by the HL_M and HL_L groups in terms of grip comfort (see Figure 3.3). Although the HL × P_{TH} interaction effect was also significant (p = .001), all treatments were placed in the same group during post hoc analysis. P_{WD} also demonstrated a significant effect (p = .003). The post hoc analysis showed that the 70-mm width belonged to group A with the 65-mm width, which had the highest mean (SD) GC_{OV} of 4.7 (1.2). Overall, the highest and second-highest grip comfort in terms of both GC_{WD} and GC_{OV} were commonly observed at P_{WD} = 65 mm and 70 mm, respectively. The effect of P_{WD} on PD_{AT} was significant (p < .0001), and the post hoc analysis showed that the 65-mm treatment belonged to group A with the 70-mm treatment, which had the highest mean (SD) PD_{AT} of 4.8 (1.4) (see Figure 3.4).

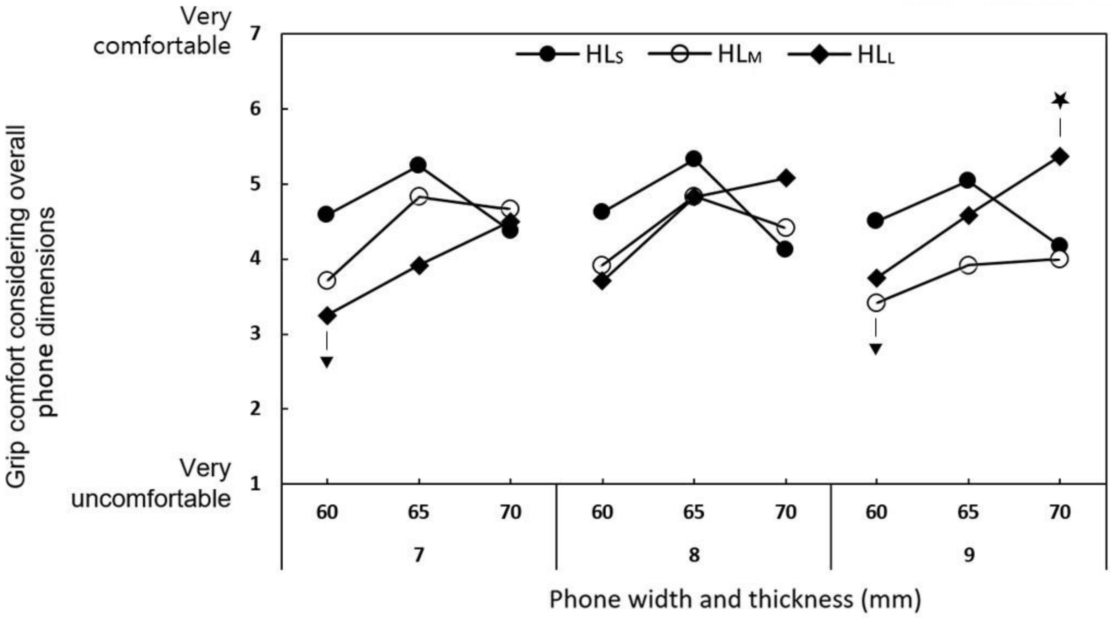


Fig. 3.3 Effects of hand length, phone width, and phone thickness on grip comfort considering overall dimensions (★: highest grip comfort and in group A; ▼: not in group A; SD range: 0.9–1.8)

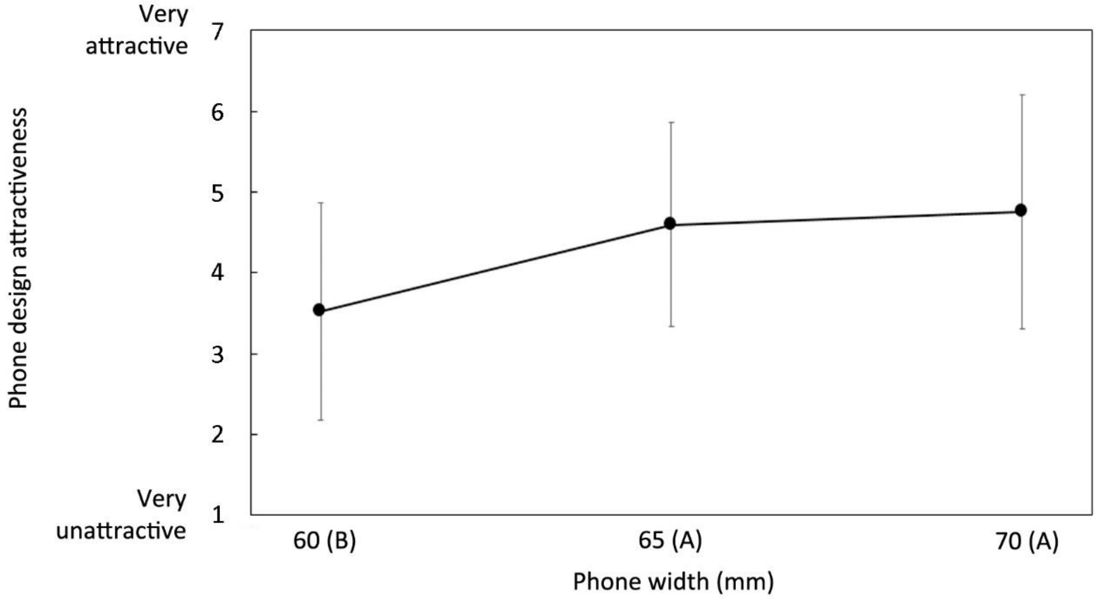


Fig. 3.4 Effects of phone width on phone design attractiveness (Tukey's HSD grouping is indicated in parentheses; SD range: 1.3–1.4)

3.3.3. Associations between dependent variables

The bivariate correlations between the four dependent variables used in Stage II were all positive and within a .34–.77 range (see Figure 3.5). GC_{OV} exhibited high positive correlations (.60–.77) with PD_{AT}, GC_{WD}, and GC_{TH}. PD_{AT} showed a high positive correlation with GC_{WD} ($r = .64$) but a low positive correlation with GC_{TH} ($r = .37$).

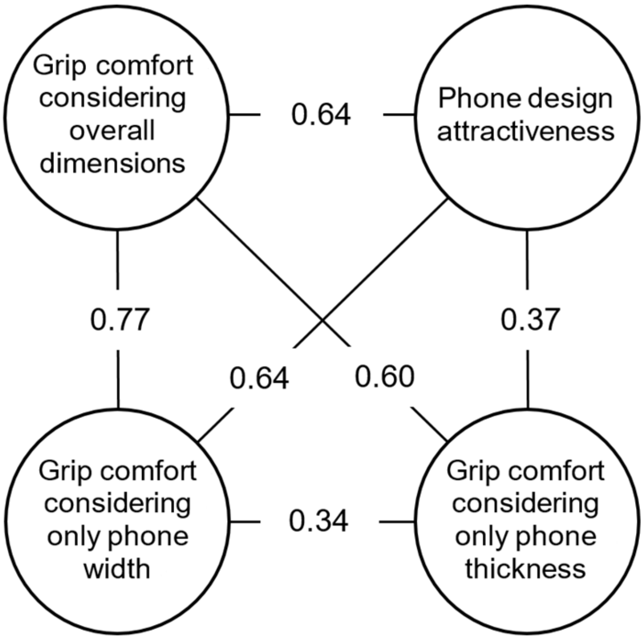


Figure 3.5 Bivariate correlations between GC_{WD} (grip comfort considering exclusively phone width), GC_{TH} (grip comfort considering exclusively phone thickness), GC_{OV} (grip comfort considering overall dimensions), and PD_{AT} (phone design attractiveness) (all p values < .0001).

3.3.4. Determination of phone mass for one-handed grip comfort (Stage III)

Using the dimensions determined in Stages I and II [140 mm (H) × 65 mm (W) × 8 mm (T) × 2.5 mm (R)], the influence of mass on grip comfort (GC_{MS}) was analyzed using smartphone mock-ups varying only in mass. The effect of P_{MS} on GC_{MS} was significant ($p < .001$; Table 3.4), with P_{MS} being divided into four groups ($M_2M_1M_3$, M_3M_4, M_5M_6, and M_6M_7; see Figure 3.6). M_2 (122 g), M_1 (106 g), and M_3 (137 g) were suitable for grip comfort, with their mean (SD) GC_{MS} values being 5.3 (1.1), 5.2 (1.5), and 4.6 (1.2), supporting H3.

Table 3.4 Main and interaction effects of hand length (HL) and phone mass (P_{MS}) on grip comfort.

	HL	P_{MS}	HL × P_{MS}
p-value	0.19	<0.001*	0.15

F-ratio	$F_{2, 33}$ = 1.744	$F_{6, 198}$ = 67.289	$F_{12, 198}$ = 1.443
partial η^2	0.096	0.671	0.080

*p values below 0.05

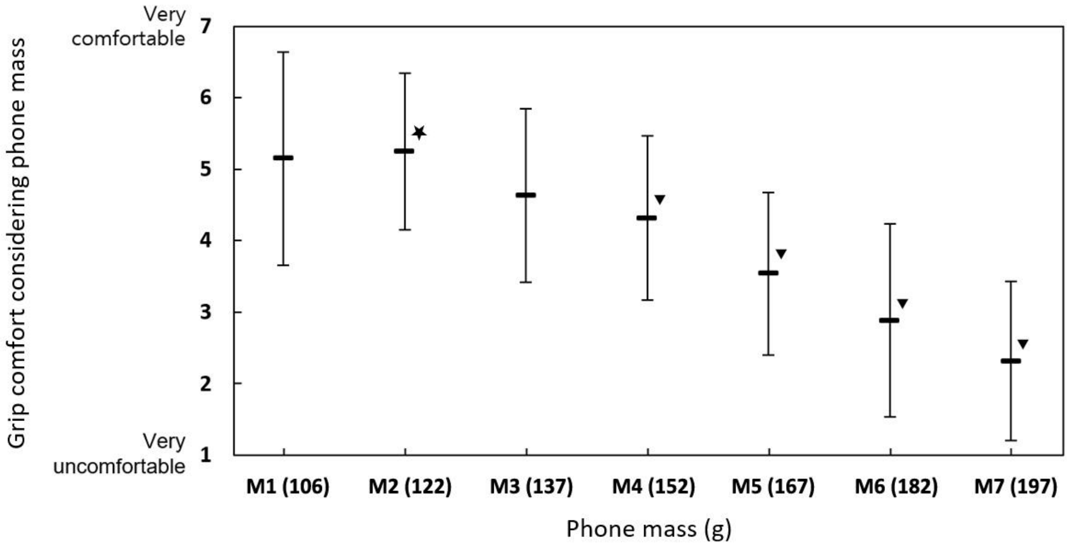


Figure 3.6 Effects of phone mass on grip comfort with phone dimensions fixed at 140 mm (H) × 65 mm (W) × 8 mm (T) × 2.5 mm (R) (★: highest grip comfort and in group A; ▼: not in group A; error bars indicate SDs).

3.4. Discussion

This study examined the main and interaction effects of hand length and smartphone specifications on grip comfort and design attractiveness. This section provides further comments on the obtained results and compares them to the results of previous studies. The limitations of the current study are also discussed.

3.4.1. Comparison between the experimental results and existing smartphones

The ranges of height and width which provided the high grip comfort in Stage I were described in Figure 3.7. The device dimensions that provided the best grip comfort in Stage II, 140 mm (H) × 65 mm (W) × 8 mm (T) × 2.5 mm (R), are smaller than the mean dimensions of the 52 smartphone models released in South Korea between 2013 and 2015 [144.1 mm (H) × 73.2 mm (W) × 8.4 mm (T)] as well as the mean dimensions of 286 smartphone models released worldwide by the top five manufacturers during the same period [139.6 mm (H) × 71.4 mm (W) × 9.2 mm

(T)]. This suggests the mean dimensions of current smartphone devices are slightly too wide to provide onehanded grip comfort. A data comparison of the two markets showed they differed in terms of phone height ($p = .008$ for the unpaired t test), but not width ($p = .075$; see Figure 3.7). It should be noted that phone width was the most important dimension for grip comfort in the current study.

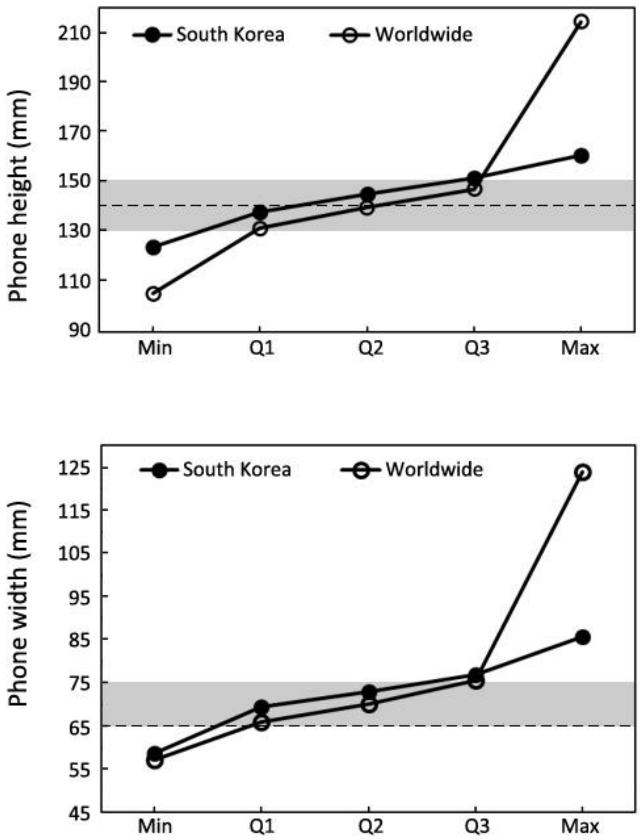


Figure 3.7 Comparison of height and width dimension min, max, and quartile values from 52 smartphone models released in South Korea and 286 models released worldwide between 2013 and 2015. Shaded areas are the ranges of device height and width to provide high grip comfort in Stage I. Dotted lines indicate the dimensions of device height and width to provide the highest grip comfort in Stage II.

3.4.2. Bivariate correlations between grip comforts and design attractiveness

Grip comfort depended more strongly on phone width than thickness in the current study, supporting H1. The effects of P_{WD} on GC_{WD}, GC_{OV}, and PD_{AT} were significant in Stage II; however, the effect of P_{TH} was not significant. Moreover, the bivariate correlations among GC_{OV}, GC_{TH}, GC_{OV}, and PD_{AT} were all positive (0.34–0.77), with GC_{OV} and GC_{WD} exhibiting the highest correlation ($r = .77$). In the P_{TH} range 7–9 mm, changes in phone thickness went unnoticed from a grip comfort perspective. The optimal width range for grip comfort (P_{WD} = 65–70 mm) was equal to the optimal width range for PD_{AT}. Additionally, GC_{OV} and PD_{AT} exhibited a high positive correlation (r = 0.64). Although the interaction effect of $P_{WD} \times P_{TH}$ on GC_{TH} was significant, the post hoc test showed all examined values were contained in a single group, partially supporting H2. The mean GC_{TH} was relatively high across phone widths of 60–70 mm (≥ 4.64) with thicknesses of 7–8 mm; however, it tended to decrease across phone widths of 60–65 mm (≤ 4.33) with thicknesses of 9 mm.

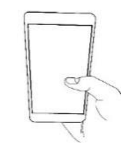
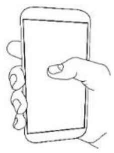
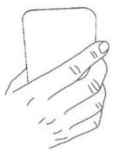
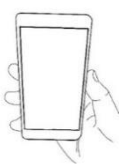
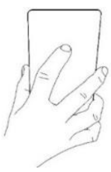
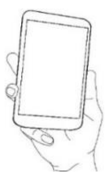
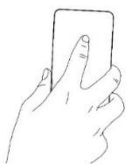
In this study, grip comfort and design attractiveness were evaluated in a multimodal context in which both haptic and visual information were presented together. As described above, the device width optimizing grip comfort (in which haptic information is of relatively greater importance) coincided with the width maximizing design attractiveness (in which visual information is of greater relative importance). These results indicate haptic and visual information complement each other and are both important in determining the grip comfort and design attractiveness of a smartphone. Indeed, Ernst and Banks (2002) demonstrated that people combined visual and haptic information to estimate object size more effectively. Similarly, Zhou, Niu, and Wang (2015) reported that operating comfort, determined by phone material, size, and shape, influenced perceived appearances as well as external factors such as shape attractiveness and layout rationality.

3.4.3. Effects of smartphone shape and task on grip posture

When using a hand-held device, users select a grip posture considering the object, the task, and their hand (Cutkosky 1989, Lee et al. 2016). Previously, grasps have been classified by task or object characteristics. The classifications of Napier (1956) included “power grip” for stability and security, “precision grip” for sensitivity and dexterity, and “combined grip” (radial fingers positioned for precision grip and ulnar fingers for power). Cutkosky and Howe (1990) further divided the power and precision grips into nine and seven subcategories, respectively, considering object characteristics. Other grip postures include the “lateral pinch” (gripping an object with the thumb and index finger in a “power grip” position to make an additional motion such as spinning a key; Schlesinger, 1919; cited in Cutkosky & Wright, 1986), “dynamic grip” (interacting with an object using fingers while holding it such as pushing a button on a spray can; Kapandji, 1982), “precision handling” (extended metacarpophalangeal joints and flexed interphalangeal joints; Landsmeer, 1962), and “digital manipulative pattern” (a subcategory of precision handling; Elliott & Connolly, 1984). Smartphone grip postures also vary according to tasks (smartphone applications; Chang et al., 2006) and require a proper combination of power and precision to hold the device and achieve the intended interactions, resembling dynamic grips.

The calling task requires a firm grip and is critical in determining overall smartphone grip comfort. Lee et al. (2016) defined five types of one-handed smartphone grips (Table 3.5) differing by the contact regions between the glabrous hand skin and the device, the fingers involved, and the power- or precision-oriented nature. Among these five, the "holding lateral sides with fingers and thumb" grip resembles a typical voice call grip; however, the latter requires a firm and dynamic (e.g., for volume button control) grip. In the first three smartphone grip postures, the smartphone is laid on or loosely held by the hand while the thumb is used for touch interactions. Hence, these three grips (involving non-firm dynamic grips) are less sensitive to smartphone dimensions relative to voice call (firm, dynamic) grips.

Table 3.5 Five representative grasp postures used for one-handed smartphone front or rear interactions (adapted and expanded from Lee et al. (2016))

Grasp posture			Interaction area	Digit used for interaction	Grasp type	Contact regions of hand and device
		Holding phone with fingers and palm	Front	Thumb	Non-firm dynamic grip	Palm and fingers contact one lateral side and the rear.
		Supporting bottom with little finger	Front	Thumb	Non-firm dynamic grip	Palm and fingers contact one lateral side and the rear while the little finger supports the bottom.
		Holding lateral sides with fingers, palm, and thumb	Front	Thumb	Non-firm dynamic grip	Palm contacts one lateral side while the distal parts of all four digits (excluding thumb) contact the opposing lateral side.
		Holding lateral sides with fingers and thumb	Rear	Index	Firm dynamic grip	Thumb contacts one lateral side while the distal portions of the middle, ring, and small fingers contact the other side. Index finger touches the rear.
		Supporting bottom with little finger	Rear	Index	Firm dynamic grip	Thumb contacts one lateral side while distal parts of the middle and ring fingers contact the opposing lateral side and the little finger supports

the bottom. The index finger touches the rear.

3.4.4. The best specifications of smartphone for high grip comfort

The previous studies on suitable widths or circumferences for hand-held tools were conducted with respect to grip force or perceived comfort. Similar to current results, Chowdhury and Kanetkar (2017) reported the most preferred mobile phone width was 70 mm. Blackwell et al. (1999) found circumferences of 140–160 mm provided high grip force, whereas Kong and Lowe (2005) found cylindrical handles with circumferences of 116–151 mm provided maximal perceived comfort. These circumference ranges correspond to widths of 50–72 mm for an 8-mmthick bar-shaped object. The overlapping range from both studies, 140–151 mm, likely provides both high grip force and perceived comfort. Smartphones 65 mm wide and 8 mm thick, or with a perimeter of 146 mm (= ((65W – 2 × 2.5R) + (8T − 2 × 2.5R)) × 2 + (2 × π × 2.5R)), provided the highest grip comfort in the current study. This value falls within the 140–151 mm range mentioned above, indicating that perimeters associated with high grip comfort are consistent across two object shapes (cylinder and parallelepiped).

The smartphone with the second-lightest mass (122 g) provided the highest grip comfort. This observation suggests a specific mass is associated with high grip comfort, supporting H3. Of note, the haptic perception of object masses can be affected by visually perceived object sizes: this size–weight illusion explains why larger object may be perceived as lighter than smaller objects even if they are equal in mass (Charpentier, 1891, as cited in Jones & Lederman, 2006). This study determined the smartphone dimensions and mass that provide the greatest one-handed grip comfort. Additional research will be required to determine the optimal mass for a smartphone design focused on screen size (e.g., a phablet) rather than one-handed grip comfort.

3.4.5. Limitations

This study encountered several limitations. First, only the South Korean population was considered. Although South Korean adults with a wide range of hand lengths (14.5th to 92nd percentiles) were considered and the effect of hand length was not significant in this study, it is still necessary to verify whether the results of this study can be generalized to other ethnic groups or individuals with more extreme hand sizes. Second, this study considered only individuals in their 20s. As both tactile sensitivity and grip force of the hand decrease with age (Thornbury & Mistretta, 1981), older individuals are expected to be less sensitive to grip comfort; however, it remains necessary to examine whether grip comfort needs are altered in an older population. Third, although there may be diverse factors affecting the grip comfort and design attractiveness of smartphones, this study focused on only the major phone dimensions (phone height, width, thickness, edge roundness) and mass. The shape and location of screen curvature, for example, could also affect grip comfort (Yi et al., 2017). Fourth, the design attractiveness of a smartphone can be affected not only by the size of the device but also by various other factors such as color, novelty, brand, and other form factors (e.g., display ratio, button shapes and sizes, and materials; Chuang, Chang, & Hsu, 2001; Shinder, 2010; Hassan, 2015). Fifth, longer-term grips should also be considered: whereas this study investigated short-term grips, previous studies on grip comfort have used durations ranging from 3 s to 10 min. Although the 10-s grip duration used in this study is not too short, additional research is required to investigate longer-term grips. Sixth, it is necessary to investigate smartphone dimensions that provide high grip comfort for touch interaction tasks. However, in the case of the grip posture for touch interaction, the smartphone is laid on (or loosely held by) the hand while precise thumb movements are used for touch interactions. Because no firm grip is involved in this grip posture, nonextreme smartphone dimensions are less likely to affect grip comfort. Conversely, because a firm grip is required during voice calls, smartphone dimensions are more likely to affect grip comfort during voice calls (as demonstrated in this study). Finally, the findings of this study were based on subjective grip comfort and design attractiveness ratings. By the knowledge of these authors, no validated objective measurement for grip comfort has been reported in relevant literature. Neither Ahn, Kwon, Bahn, Yun, & Yu (2016) nor Lee et al. (2016) discovered significant associations between muscle activities and perceived discomfort, indicating muscle activities are insufficient for explaining physical discomfort. It is thus worthwhile to discover new objective measurements capable of effectively explaining grip comfort. Although future studies are necessary to address the above limitations, the findings of this study remain useful for improving one-handed smartphone grip comfort and design attractiveness.

3.5. Conclusion

This study involved the investigation of the effects of smartphone dimensions (height, width, thickness, and edge roundness) and mass on one-handed grip comfort and design attractiveness. The dimensions optimizing grip comfort and design attractiveness were 140 mm (H) × 65 mm (or

70 mm) (W) × 8 mm (T) × 2.5 mm (R) across three tested hand-length groups, and the most preferred mass was 122 g (from a range of 106–137 g). Width had the greatest influence on grip comfort and design attractiveness from the four investigated smartphone dimensions. In this study, a 146 mm horizontal perimeter was associated with high grip comfort and design attractiveness. This value lies in the middle of the cylindrical handle circumference range that has previously demonstrated high grip force and comfort (140–151 mm). These findings will contribute to the development of more ergonomic and aesthetically pleasing smartphones.

Chapter 4. [Study 3] Future Mobile Display Devices: Foldable Display Devices

4.1. Introduction

Foldable display devices, compact mobile devices featuring large screens, are expected to follow flat and curved display devices onto the commercial market shortly (Davies, 2016; Prabhu, 2017). The current smart devices can be divided into three groups by screen size: screens < 5" (12.7cm) operated predominantly with one hand, screens 5–6" (12.7-15.2cm) involving one- or two-hand operations [i.e. phablet (phone + tablet) phones], and screens > 6" (15.2cm) requiring two-handed operations (i.e. tablet PCs). This smart device diversity is attributed to the limitations of a single device in meeting diverse user needs (compact size, easy one-hand operation, and large screen). Indeed, some people possess more than one smart device (Anderson, 2015), and use their devices alternately (e.g. a large-screen device for watching videos and a small-screen device for instant messaging; Google Inc., 2012).

Large screens provide both advantages and disadvantages. Large screens can improve usage adoption (Kim and Sundar, 2014), legibility, and immersion (Lin et al., 2013; Duchnicky & Kolers, 1983; Thompson et al., 2012). Compared to small screens, large screens facilitate improved comprehension and faster reading of on-screen information by providing a larger amount of information at a time, hence requiring less scrolling (Chan et al., 2014, Sanchez & Wiley., 2009). In addition, large on-screen buttons can reduce input errors (Sun et al., 2007; Sesto et al., 2012) and wrist extension (Kim et al. 2014). Conversely, large screens provide poor operability (Chiang et al., 2013), grip comfort (Lee et al., 2018), and portability. Similarly, Tablet PCs with a large screen can induce high shoulder and neck fatigue (Pereira et al., 2013) and neck pain (Vasavada et al., 2015). In a study by Lee et al. (2018), a 140H × 65W × 8T × 2.5R (mm) smartphone, or approximately 120H x 60W mm (5.3" or 13.5cm) screen size, provided high one-handed grip comfort and attractive design. Most people, however, prefer larger mobile phones to smaller ones, favoring visual effects over grip comfort (Chiang et al., 2013). A well-designed foldable display device could meet the paradoxical requirement for improving both grip comfort and visual effects.

Previous studies on foldable devices focused on defining new input methods using screen folding. Schwesig et al. (2004) suggested an input method utilizing simple screen bending, and Lahey et al. (2011) determined six preferred gestures for bending screen corners. Gallant et al. (2008) developed foldable user interfaces and proposed eight bending or folding methods. Using an E Ink (E Ink Holdings, Inc., MA, USA), Gomes et al. (2013) developed a notification system that used full-screen bending and screen corner bending. Full-screen bending was suitable for urgent message notifications, whereas corner bending was used for non-urgent tasks such as emails. Lee et al. (2010) examined the effects of materials (plastic sheet, paper, and elastic cloth) on preferences in user-defined folding gestures. Paper and elastic cloth were preferred for performing ‘off’ (closing current content), ‘open’ (loading new content on screen), and ‘scrap’ (scrapping the current page and saving it in the scrap folder) functions. Khalilbeigi et al. (2012) proposed folding interactions differing in folding direction, folded position, and synchrony between folding and touching. Tan et al. (2015) studied effective methods for providing affordance using screen folding method and direction. Lee et al. (2008) proposed four flexible display concepts resembling a newspaper, scroll, fan, and umbrella. Though these previous studies developed new input methods using display foldability, little information exists regarding preferred screen sizes and folding methods for foldable display devices considering display size, task, and hand length.

The current study had two objectives: first, to determine suitable screen sizes for five representative smartphone tasks (instant messaging, calling, texting, web searching, and gaming) on mobile foldable display devices considering a wide range of hand lengths, and second to determine preferred folding methods for the determined screen sizes. Diverse foldable display device concepts were considered, ranging in size from smartphones to tablet PCs.

4.2. Material and methods

4.2.1. Participants

Thirty young individuals with a mean (SD) age of 21.6 (2.2) years participated in this study. Each had a minimum experience of two years of using smartphones, with a mean (SD) use experience of 4.6 (1.5) years. All were right-handed and healthy without any musculoskeletal diseases affecting their wrists. Additional efforts were made to recruit a group of individuals with a wide range of hand lengths. This study was approved by the local institutional review board (IRB). All participants were compensated for their time.

Table 4.1 Participant groups and hand lengths

	Short hand (≤165.6 mm†)	Medium hand (173.6–178.6 mm†)	Large hand (≥186.6 mm†)	Total
Number of participants	10 (1:9)	10 (5:5)	10 (10:0)	30 (16:14)

(male:female)

†165.6 mm, 173.6 mm, 178.6 mm, and 186.6 mm correspond to 30th, 45th, 55th, and 70th percentiles, respectively, according to SizeKorea (2004).

4.2.2. Experimental design

The current study consisted of two stages. Stage I determined preferred screen sizes considering hand lengths (Hand; between-subjects factor), smartphone tasks (Task; within-subjects factor), and screen sizes (Screen; within-subjects factor). A 3 (Hand) × 5 (Task) × 3 (Screen) mixed factorial design was used. Participants were divided into three groups based on the hand length data (SizeKorea, 2004) of South Koreans 20–50 years old: $Hand_S$ (small hand; ≤165.6 mm, 30^{th} percentile), $Hand_M$ (medium hand; 173.6–178.6 mm, 45^{th}–55^{th} percentile), and $Hand_L$ (large hand; ≥186.6 mm, 70^{th} percentile). Intergroup hand length differences were at least 8 mm. The five tasks used in this study were determined by referring to relevant reports (KISDI, 2011, DMC Report, 2013, KISA, 2014, KISDI, 2015, KISDI, 2016, Chaffey, 2018): 1) instant messaging ($Task_{MSGR}$), 2) calling ($Task_{CALL}$), 3) texting ($Task_{SMS}$), 4) web searching ($Task_{SEARCH}$), and 5) gaming ($Task_{GAME}$). For $Task_{MSGR}$ and $Task_{GAME}$, KakaoTalk (Kakao Corp., 2016) and Crossyroad (Hipster Whale Corp., 2016) were used, respectively, based on their Google Playstore™ popularity. Screens were divided into three groups: $Screen_S$ (a small screen of 120 height (H) × 60 width (W) or a device of 140H×65H×8 thickness (T) mm), $Screen_M$ (a medium screen of 120H×128W or a device of 140H×130W×4T mm), and $Screen_L$ (a large screen of 120H×196W or a device of 140H×198W×2.7T mm). Small, medium, and large screens correspond to 5.3" (13.5cm), 6.9" (17.5cm), and 9.0" (22.9cm) screens, respectively. Considering 140H×65W×8T×2.5R smartphones provided high one-handed grip comfort and attractive design in a study by Lee et al. (2018), the current study determined $Screen_S$ to be 120×60 mm, assuming that top/bottom and side bezel widths were 10 and 2 mm, respectively. The sizes of $Screen_M$ and $Screen_L$ were, respectively, two and three times that of $Screen_S$, with additional margins as required for screen folding (Figure 4.1). Stage I used full flat screen conditions as a full screen size is still required when a task is performed with the screen unfolded, partially folded, or full folded.

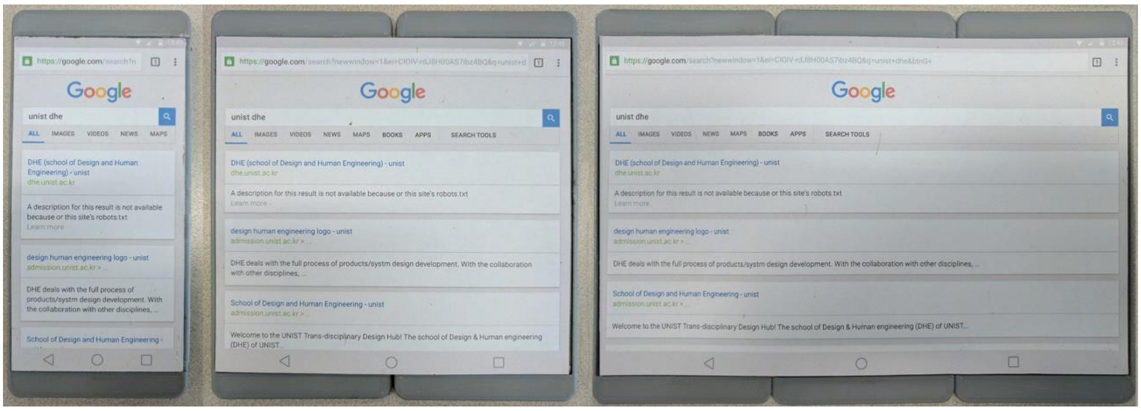
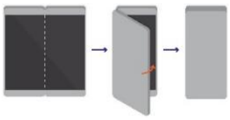
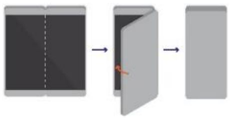
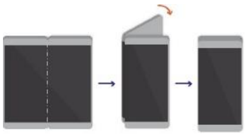
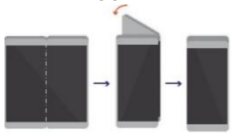
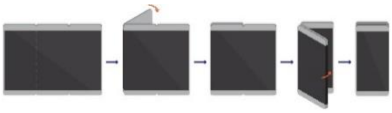
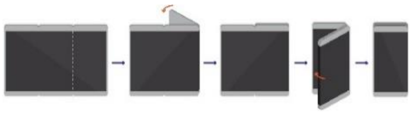
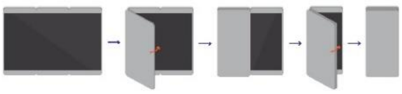
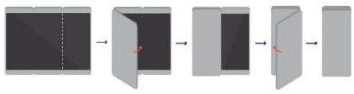
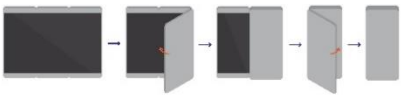
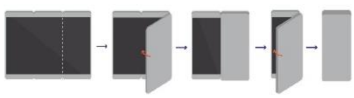
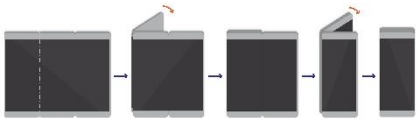
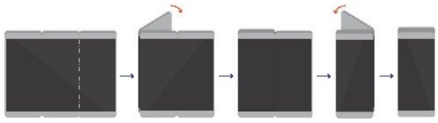
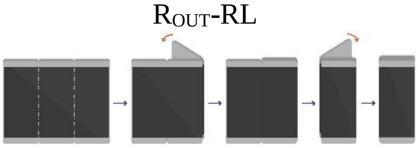
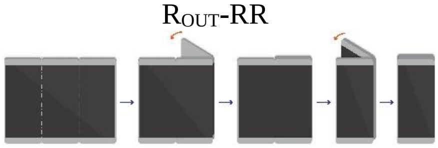


Figure 4.1 Foldable smartphone prototypes with small, medium, and large screens used to determine preferred screen sizes considering hand length, smartphone task, and screen size in Stage I. Screens for web searching ($Task_{SEARCH}$) are shown.

Stage II identified the user-preferred folding methods and most preferred device concept considering hand length and folding methods (Fold; within-subjects factor). The three hand-length groups were defined as described in Stage I. Bi-fold and tri-fold concepts involving one or two screen folds were considered to develop foldable devices that resemble current non-foldable smartphones when folded. Each folding concept was further divided according to screen locations (inside or outside) and fold lines (left or right side) after folding. These factors are important as they can affect folding/unfolding comfort and influence the external design and layout of some device parts (e.g. cameras, speakers, and mics). Five concepts were defined accordingly: two bi-fold concepts (V-infold type and V-outfold type) and three tri-fold concepts (Z-type, R-infold type, and R-outfold type). Fourteen folding methods (Fold) were derived using these five concepts (Table 4.2). The screen of the V-infold type (V_{IN}) folds inward and is hidden inside after folding whereas the screen of the V-outfold type (V_{OUT}) folds outward, remaining outside. V_{IN} and V_{OUT} were classified into two sub-types based on fold line positioning: V_{IN}-L, V_{IN}-R, V_{OUT}-L, and V_{OUT}-R (-L indicates fold lines located on the left side after folding, and -R on the right). ‘Z-type’ screens folded in a Z-shaped configuration, and were further classified into Z-L and Z-R. ‘R-type’ screens folded twice inwardly (R_{IN}) or twice outwardly (R_{OUT}), defined by the display location after folding. R_{IN} and R_{OUT} were each further classified into four categories based on fold line positions: R_{IN}-LL, R_{IN}-LR, R_{IN}-RL, R_{IN}-RR, R_{OUT}-LL, R_{OUT}-LR, R_{OUT}-RL, and R_{OUT}-RR.

Table 4.2 Folding concepts and variant folding methods (Stage II)

Folding concepts [Height×Width ×Thickness (mm), Mass (g)]		Folding methods	
Bi-fold	V_{IN} (140×130 ×4, 92)	V_{IN}-L 	V_{IN}-R 
	V_{OUT} (140×138 ×4, 88)	V_{OUT}-L 	V_{OUT}-R 
Tri-fold	Z (140×200 ×2.7, 117)	Z-L 	Z-R 
	R_{IN} (140×200 ×2.7, 125)	R_{IN}-LL 	R_{IN}-LR 
		R_{IN}-RL 	R_{IN}-RR 
	R_{OUT} (140×209 ×2.7, 116)	R_{OUT}-LL 	R_{OUT}-LR 
		R_{OUT}-RL 	R_{OUT}-RR 

The prototypes used in this study were fabricated from Acrylonitrile Butadiene Styrene (ABS) plastic panels, paper (showing a default screen), and rubber magnets (to easily attach and detach the screen to/from the panels) (Figure 4.2). When completely folded, each prototype was 140H×65W×8T mm, selected to provide high one-handed grip comfort and attractive design (Lee et al., 2018).

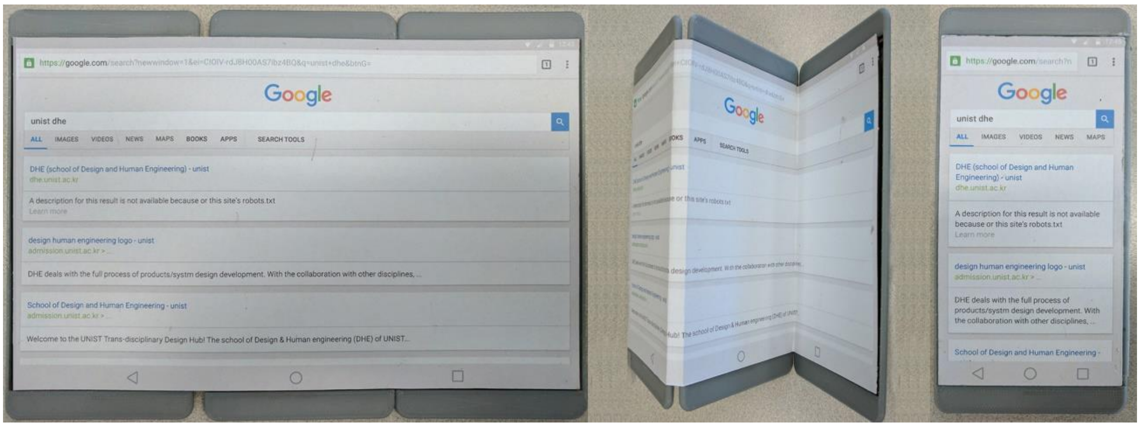


Figure 4.2 Foldable smart device prototypes used in Stage II (Z-L case). Web searching screen is shown (Task$_{SEARCH}$).

4.2.3. Data collection and processing

First, participants were informed of the objectives and procedure of this study, and their personal information (age, sex, and hand length) was obtained. Sitting at a desk, one of smartphone use contexts (Lee et al., 2016), was considered in this study. Accordingly, stages I and II used a desk (1500×600×730 mm) and a height-adjustable chair. To determine the proper screen sizes for the five tasks, each task was performed on three non-foldable mock-ups (Stage I), sized Screen$_{S}$, Screen$_{M}$, and Screen$_{L}$. After a 5 min trial use of each prototype involving simulated texting, swiping, and touching, the 15 treatments (5 Tasks × 3 Screens) were randomly presented. Each task was simulated using the prototypes with printed screens. Accordingly, participants simulated typing by touching on a messenger application screen for Task$_{MSGR}$ and on the default message application screen for Task$_{SMS}$, calling by holding each prototype on the ear for Task$_{CALL}$, scrolling the screen and selecting an article for TaskS$_{EARCH}$ and playing a game by touching a game application screen for Task$_{GAME}$. Regarding the 30 s gripping requirement for each prototype in each task, participants rated the screen size suitability on a 100-mm visual analogue scale (0: Too small, 100: Too large) (VAS) (Q1). Following a 5 min break, the folding/unfolding comfort of each folding method was evaluated and preference rankings were given for bi-fold concepts, tri-fold concepts, and overall (Stage II). First, each participant freely used the prototypes by folding/unfolding the screen and performing simulated touching and typing for 5 min. Next, the 14 folding methods were randomly presented for the folding/unfolding comfort evaluation. Participants freely unfolded and folded and initially fully folded mock-ups. For tri-fold concepts, both partly and fully unfolded states were considered. Each participant rated the comfort of each folding method (based on 30 s folding/unfolding) on a 100 mm VAS (0: Very uncomfortable, 100: Very comfortable) (Q2). Next, two bi-fold concept prototypes (or three tri-fold concept prototypes) were provided to determine preference rankings within the bi-fold (or tri-fold) concept prototypes. After using the prototypes for 2 min (folding/unfolding the screen and performing simulated touching and typing), each participant indicated their preference between V_{IN} and V_{OUT} (Q3) [or Z, R_{IN}, and R_{OUT} (Q4)] based on an overall evaluation considering the folding/unfolding comfort, design attractiveness, screen size, screen location, and durability, then stated their reasoning. Finally, the most preferred concept was selected from the two concepts chosen in Q3 and Q4, and their reasoning was stated (Q5). The total required time for Stages I and II was approximately 30 min each.

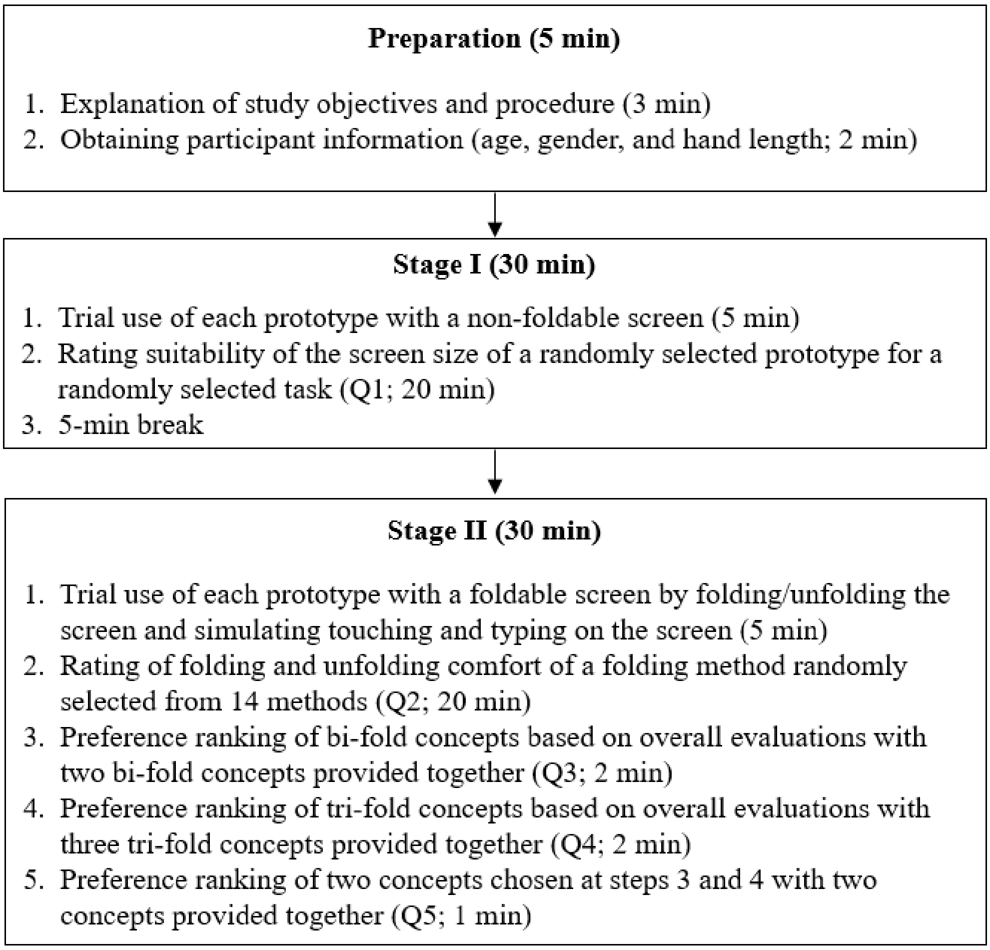


Figure 4.3 Two-stage experimental procedure (Steps 3 and 4 in Stage II were randomly presented)

4.2.4. Data analysis

A 3×3×5 mixed factor analysis of variance (ANOVA) was used to examine the main and interaction effects of Hand, Task, and Screen variables on screen size suitability, as considered in

Stage I (regarding Q1). A 3×14 mixed factor ANOVA was used to examine the main and interaction effects of Hand and Fold on folding and unfolding comfort (related to Q2). When ANOVA indicated a main or interaction effect was significant, a Tukey's honestly significant difference test was performed as a post-hoc test. Regarding preference rankings (related to Qs 3–5), the percent ratios [(number of votes received / total number of votes) × 100] were compared between the prototypes. Additionally, a Fisher exact test was used to examine the preference transition between bi-fold and tri-fold concepts using the number of votes for all three hand-length data as well as for each hand-length data. JMP™ (v12, SAS Institute Inc., NC, USA) was used for all statistical analyses. Significance was concluded when $p < 0.05$.

4.3. Results

This section describes the results of ANOVA (Table 4.3) and post-hoc test results regarding the suitability of the screen size (Q1) and folding and unfolding comfort (Q2). The results of bi-fold (Q3), tri-fold (Q4), and overall (Q5) preference ratio comparisons are presented. Finally, Fisher exact test results for the preference transition between bi-fold and tri-fold concepts are described.

Table 4.3 P-values for hand length, smartphone task, and screen size effects on screen size suitability (Stage I) and hand length and folding method effects on folding and unfolding comfort (Stage II).

	Hand	Task	Screen	Fold	Hand× Task	Hand× Screen	Task× Screen	Hand× Fold	Hand× Task× Screen
Stage I	0.081	<0.0001*	<0.0001*	-	0.68	0.087	0.0006*	-	0.65
Stage II	0.45	-	-	<0.0001*	-	-	-	0.35	-

4.3.1. Determining suitable foldable screen sizes for each task (Stage I)

The Screen×Task interaction effect on screen size suitability (Q1) was significant (p = 0.00006). Two of 15 treatments ($Screen_M \times Task_{SEARCH}$ and $Screen_S \times Task_{CALL}$) were placed in group A with $Screen_M \times Task_{GAME}$, which provided the closest mean (SD) of 52.3 (8.8) to 50 (suitable). The mean (SD) of $Screen_L \times Task_{CALL}$ was highest (88.3 (11.0)), indicating the large screen was inappropriate for calling. $Screen_S \times Task_{GAME}$, $Screen_S \times Task_{SEARCH}$, and $Screen_S \times Task_{MSGR}$ were grouped with $Screen_S \times Task_{SMS}$, which provided the lowest mean (SD) at 33.4 (11.4), indicating the small screen was inappropriate for these four tasks. Although the Hand×Screen effect was not significant (p = 0.087), $Screen_L$ was found suitable for gaming in the large hand-length group with a mean (SD) of 53.3 (6.1).

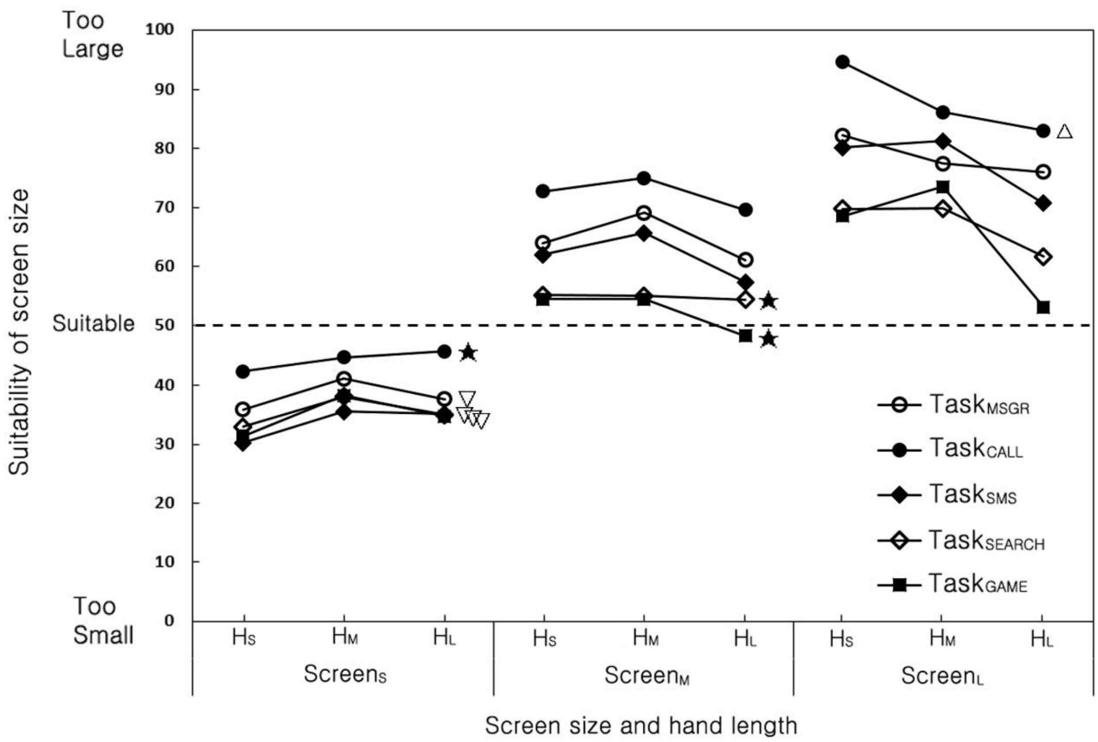


Figure 4.4 Effects of hand length, task type, and screen size on the suitability of screen size (★: 'suitable' group close to 50, △: 'too large' group close to 100, ▽: 'too small' group close to 0; SD range: 6.3~15.8).

4.3.2. Determining most preferred folding method and device concept (Stage II)

Related to Q2, Fold significantly influenced the folding and unfolding comfort of each prototype ($p < 0.0001$). The post hoc analysis grouped treatment Z-L with the V_{IN}-L condition, which exhibited the highest mean (SD) folding and unfolding comfort at 73.2 (19.1). Regarding bi-fold preference rankings (related to Q3), 21 of 30 (70.0%) testers preferred V_{IN} whereas for tri-fold concepts (Q4), 17 of 30 testers (56.7%) preferred the Z-type concept, followed by R_{OUT} (n=7 (23.3%)) and R_{IN} (n=6 (20%)). The most preferred folding concept in Q5 was Z-type (n=14 (46.7%)), followed by R_{OUT} (n=5 (16.7%)), V_{IN} (n=4 (13.3%)), V_{OUT} (n=4 (13.3%)), and R_{IN} (n=3 (10.0%)).

Regarding Q3 and Q4 combined, the Fisher exact test using all hand-length data was significant (p=0.032), indicating the preferences for bi-fold and tri-fold concepts affected each other. From the nine individuals who selected V_{IN}, five selected Z-type and four selected R_{IN}, whereas from the 21 individuals who selected V_{OUT}, 12 (40.0%) selected Z-type, seven (23.3%) selected R_{OUT}, and two (6.7%) selected R_{IN} (Figure 4.5). The Fisher exact tests for each hand-length data were not significant ($p \geq 0.07$).

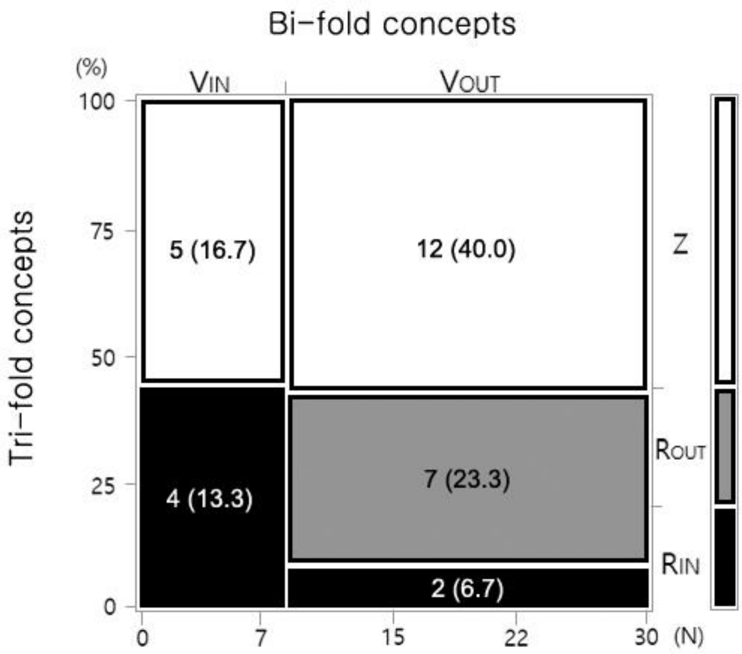


Figure 4.5 Bi-fold and tri-fold concept preference ratios (numbers within cells are the number (%) of votes for each concept)

4.4. Discussions

This study examined the main and interaction effects of hand length, screen size, and smartphone task on foldable display devices for screen size suitability (in Stage I), and preferred folding method and device concept (in Stage II). The rationale behind specific fold concept preferences were also obtained in Stage II. Further interpretation is provided, and the similarities and differences between the results of this study and previous studies are discussed below. Further, the limitations of this study are described.

Screen size suitability was task-dependent. In Stage I, the medium screen size ($Screen_M$; 6.9" or 17.5cm) was most preferred, especially for game play and web searches. The mean (SD) size suitability of the large screen ($Screen_L$) was 75.5 (15.7), indicating the 9.0" (22.9cm) screen was unsuitable for performing any of the five considered tasks. Tablet PC screens (7" (17.8cm) or larger) are thus deemed somewhat too large to perform the five major smartphone tasks. The mean (SD) size suitability of $Screen_L$ was closer to 50, or suitable, for $Task_{SEARCH}$ (67.3 (13.8)) and $Task_{GAME}$ (65.3 (15.8)) than the three other tasks ($Task_{MSGR}$ (78.8(13.0)), $Task_{CALL}$ (88.3 (11.0)), and $Task_{SMS}$ (77.7(13.4))). These two tasks are commonly performed on both smartphones and tablet PCs (KISDI, 2011; DMC Report, 2013; KISA, 2014; KISDI, 2015; KISDI, 2016; Statista, 2016). Though $Task_{SEARCH}$ and $Task_{GAME}$ appear to require a relatively wider screen than the remaining three tasks, $Screen_M$ still appeared more suitable than $Screen_L$, with mean (SD) suitability values closer to 50 (at 54.8 (6.3) and 52.3 (8.8), respectively). Though hand length failed to significantly influence any case, the large hand-length group preferred $Screen_L$ for gaming with a $Task_{GAME}$ mean (SD) size suitability for $Screen_L$ of 53.3 (6.1).

Folding method preferences depended on screen size and location. In Stage II, Q2 assessed the comfort associated with different folding/unfolding methods. V_{IN}-L (a bi-fold concept) was the most comfortable folding/unfolding method overall [mean (SD) = 73.2 (19.1) vs. 32.5 (19.9) for V_{IN}-R]. This method allowed participants to naturally fold and unfold the device with their left hand while holding it with their right hand. The tri-fold Z-L concept, which folds and unfolds similar to V_{IN}-L with the device held in the right hand and manipulated with the left, provided the second highest folding/unfolding comfort. However, Q3 indicated 21 (70%) participants preferred V_{OUT} to V_{IN} for bi-fold types with considerations of portability, screen size, folding/unfolding comfort, and design attractiveness. Though the structure of V_{IN} can protect the screen from external impacts, it is inconvenient to unfold the device to view the screen. The screen of V_{OUT} is always exposed, and hence more vulnerable to scratches and external impacts; however, participants commented 'V_{IN} is inconvenient because it is impossible to see the screen in a folded state.' Two other advantages of V_{OUT} were 'you can get a visual notification such a quick alarm even if the screen is locked' (21 participants (70%)), and 'the side screen (the folded screen part) and the rear screen of V_{OUT} can be potentially used for both input and output' (eight participants (26.7%)).

Interesting patterns were observed in the preference transitions between bi-fold and tri-fold concepts for each individual. Over half of V_{IN} and V_{OUT} selectors preferred Z-type (5 (55.6%) for V_{IN} and 12 (57.1%) for V_{OUT}). All V_{IN} and non-Z-type selectors (44.4%) preferred R_{IN}; however, two V_{OUT} and non-Z-type selectors (9.5%) chose R_{IN} whereas seven (33.3%) chose R_{OUT}. Both V_{IN} and R_{IN} screens are folded inside, whereas V_{OUT} and R_{OUT} screens remain outside. Z-types featured both V_{IN} and V_{OUT} concepts. Four V_{IN} and R_{IN} selectors considered 'screen protection' more important, whereas seven V_{OUT} and R_{OUT} selectors valued 'all-time visible screen' more.

These two factors appear to compete with each other, influencing individual preference transitions across bi-fold and tri-fold concepts.

Additionally, the V_{OUT} concept could provide ergonomic rear interactions relative to existing smartphones with rear interactions. Lee et al. (2016) investigated the effects of task type, phone width, and hand length on rear interaction index finger reach zones and recommended an ergonomic rear interaction zone. Lee et al. (2016) and Lee & Kyung (2017), using five and 140 smartphones, respectively, demonstrated that rear interaction zones on tested models had little overlap with this recommended zone. As rear interactions currently function using a manual button, a touchpad, or a sensor, the rear interaction zone is defined by the size of a given physical feature and cannot accommodate diverse hand sizes. In contrast, the entire rear screen of V_{OUT} models could provide an adjustable rear interaction zone.

The Z-type was selected as the most preferred folding concept in Q4 (preference ranking of three tri-fold concepts) and Q5 (preferred concept between those chosen in Q3 and Q4). Regarding Q4, participants expressed Z-type advantages such as ‘the Z-type provides the most intuitive folding and unfolding method’ (17 participants (56.7%)), ‘its design is similar to existing smartphones and its screen can be expanded’ (ten participants (33.3%)), and ‘it provides three different screen sizes, from a small screen, similar to a typical smartphone screen, a medium screen, to a large screen’ (five participants (16.7%)). A commonly addressed R_{IN} and R_{OUT} disadvantage was ‘I can easily fold this incorrectly, and then I have to unfold and fold it again’ (four participants (13.3%)), and it was noted for R_{IN} ‘the screen of R_{IN} cannot be used when folded, similar to V_{IN}’ (six participants (20.0%)). The Z-type in Q5 included the V_{OUT} form and provided three different screen sizes. Fourteen participants (46.7%) commented, ‘Z-type is good because its screen size can be expanded to that of a tablet PC’. Considering that Stage I found $Screen_M$ to be more suitable for tasks than $Screen_L$, users appear to desire a greater screen size flexibility than is actually needed.

The current study encountered some limitations. First, this study used low-fidelity prototypes as foldable displays are unavailable. Although formative usability evaluations using low-fidelity prototypes (e.g. paper prototypes) are effective in user experience studies when actual products are absent (Snyder, 2003), these findings must be verified using actual foldable displays. User experiences (e.g. operating comfort, learnability, and usability) can be better assessed using actual products (Zhou et al. 2015). Second, smartphone weight was not considered. The used mock-ups were equal in size when folded, but differed in weight (88–125 g). As demonstrated by Lee et al.

(Submitted), perceived grip comfort can vary between same-sized devices of differing weights. The size-weight illusion (where larger objects of equal weight feel lighter than smaller ones; Charpentier, 1891) should be considered as well as device weight, especially because the size of foldable display devices is changeable. Third, all participants were right-handed. Though approximately 90% of the population is right-handed (Holder, 2001; Hardyck & Petrinovich, 1977), left-handedness should be considered for universal designs. As folding direction influenced folding concept preferences in this study, it would be better to consider both dominances when designing foldable display devices (e.g., providing a 180° screen rotating function). Fourth, we only considered young individuals in their 20's. Therefore, it is warranted to examine if there are age-related differences in grip comfort and user preference regarding foldable display devices. With age, visual function degrades (Lockhart & Shi, 2010; Rambold, Neumann, Sander, & Helmchen, 2006) and the tactile sensitivity decreases (Thornbury & Mistretta, 1981). When using smartphones, older individuals prefer to use larger fonts compared to younger individuals (Kobayashi, et al., 2011; Wu, 2011; Zhou, Rau, & Salvendy, 2014). With wider screens, font size and UI elements (e.g. button size) can be increased further. Therefore, older individuals are likely to prefer tri-fold over bi-fold, which should be verified by an additional investigation. Fifth, as only South Koreans were considered in this study, the results might be different for other ethnic groups. Indeed, the mean (SD) Korean hand length is 1.1 cm shorter than the mean North American hand length (17.6 cm (SizeKorea, 2014) vs. 18.7 cm (Chengalur, Rodgers, and Bernard 2004)). Of note is that this study considered a wide range of South Korean hand lengths (9th-93rd percentiles or 149-205 mm), yet the hand effect was not significant. In addition, the mean size of smartphone models released in South Korea was larger than the mean size of those released worldwide (Lee et al., 2018). A further investigation involving other ethnic groups will clarify whether the findings of this study can be generalized to other ethnic groups. Sixth, screen/device orientation was not considered. Only landscape mode was considered after bi-fold and tri-fold concepts were unfolded, which was a natural transition from unfolding the prototypes in portrait mode. This study focused on the preference and grip comfort involved in bimanually folding and unfolding foldable display device concepts. Additional studies on effective GUI design considering screen / device orientation are needed. Despite these limitations, the findings of the current study will be useful for designing ergonomic mobile foldable display devices.

4.5. Conclusions

This study examined the effects of hand length, screen size, and task on the suitability of screen size and preferred screen folding methods to determine ergonomic forms for mobile foldable display devices. Across three hand-size groups, a small screen was most suitable for calling whereas the medium screen was most suitable for web searching and gaming, though the large hand-length group also liked to use large screens for gaming. Based on the above results, a foldable display device providing small-to-large screen sizes appears to be effective at accommodating user needs. Among the concepts considered in this study, the Z-type provided small-to-large screen sizes (5.3" – 9.0" or 13.5cm – 22.9cm) as well as high folding/unfolding preference. These findings will contribute to the development of ergonomic mobile foldable display devices meeting diverse user needs.

Chapter 5. [Study 4] Future Mobile Display Devices: Rollable Display Devices (Grip Region)

5.1. Introduction[3]

Following curved displays, rollable displays are expected to be on the market shortly (Huitema et al., 2008; Smith, 2018). Unlike non-flexible (flat or curved) displays, rollable displays enable compact smart devices to have expandable screens. When a rollable screen is fully retracted, the device can be conveniently hand-carried. Conversely, the rollable screen should be unrolled first to access the screen. Bilateral screen unrolling requires bimanual pulling by gripping both sides of the device and externally rotating the shoulders. The pulling force acting on the gripped region should be greater than the force of the spring for screen retraction. Therefore, sufficient grip regions should be provided on the side bezels of rollable devices to facilitate bimanual pulling.

The grip comfort of a mobile device can be influenced by the gripping method, object shape, and hand size. First, grip comfort can vary depending on the gripping method even for the same object or hand. Therefore, mobile devices should be designed to accommodate diverse gripping methods. Second, the shape of a mobile device can affect grip comfort because the sensitivity to pressure varies across the glabrous skin of the hand (Johansson and Vallbo, 1979; Johansson and Vallbo, 1983). Indeed, Yi, Park, Im, Jeon, and Kyung (2017) showed that sharp side edge design decreased the grip comfort of smartphones. In addition, hand size should be considered in grip comfort studies because the contact region between the hand and object can vary with hand size. Therefore, grip comfort studies should consider the effects and relative importance of gripping method, object shape, and hand size.

The specific gripping methods required by various tasks and object shapes can affect grip comfort. Proper grip postures are used for given tasks and objects (e.g., palmar prehension for needles (Schlesinger, 1919) and dynamic grip for sprayers and lighters (Kapandji, 1983)). When a high grip force is required (e.g., when hammering), a power grip is used, in which the thumb and other fingers are clenched. A firm dynamic grip is required for smartphone calls, whereas a non-firm dynamic grip is used for other tasks (Lee et al., 2018). In addition, more than one gripping method can be used for a given task. Lee, Kyung, Lee, Moon, and Park (2016) investigated the grip postures used for smartphone front and rear interactions and showed that three and two distinct gripping methods, respectively, were used. Choi, Jung, Park, and You (2017) identified nine

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[3] This chapter was published as an international conference paper.
Lee, S., Kyung, G.*, Choi, D., Choi, H., Hwang, K., Park, S., Kim, M., Yi, J., Kim, S. (2018) Determining ergonomic forms for rollable display devices, *18' International Annual Meeting of Human Factors and Ergonomics Society*, PA, USA.

different grip postures used to operate the hard keys of smartphones. Similarly, rollable display devices should provide comfortable grip designs to accommodate various gripping methods for bilateral screen pulling. It is therefore necessary to investigate the effects of the various grip types used for screen unrolling on grip comfort.

Object shape affects grip comfort. The grip comfort of cylindrical handles (Yakou, Yamamoto, Koyama, & Hyodo, 1997; Kong & Lowe, 2005) and span measuring equipment (Blackwell, Kornatz, & Heath, 1999; Lee, Kong, Lowe, & Song 2009) has been investigated previously. The handle circumference range recommended following these four studies was 85–160 mm. Some researchers have investigated the effects of smartphone size on grip comfort. For instance, Chowdhury and Kanetkar (2017) reported that the smartphone widths that provided optimal handiness and the preferred width were 67 mm and 70 mm, respectively. Lee et al. (2018) recommended smartphone dimensions of 140 mm height (H) × 65 mm (or 70 mm) width (W) × 8 mm thickness (T) × 2.5 mm edge roundness (R) to ensure high grip comfort and design attractiveness. To the knowledge of the authors, however, the effects of grip design on grip comfort during bilateral pulling of a rollable device have not been studied previously.

The effects of hand anthropometry (e.g., hand length) on the grip comfort of mobile devices are uncertain. Lee et al. (2016) showed that compared to individuals with medium and large hand lengths, those with small hand lengths experienced high discomfort during rear interaction with a 90-mm-wide smartphone using the index finger. Kong and Lowe (2005) identified the handle diameters that provided high grip comfort for three hand-length groups (37.3–39.6 mm, 39.6–42.0 mm, and 42.0–44.3 mm for the small, medium, and large hand-length groups, respectively). Conversely, some studies have revealed non-significant hand length effects during smartphone use. For instance, Lee et al. (2018) studied the smartphone dimensions associated with high one-handed grip comfort and attractive design and found that the hand length effect was not significant. Study 3 also investigated ergonomic forms for mobile foldable display devices, again finding that the hand length effect was not significant. However, the effects of hand length on the grip comfort of rollable display devices have not been examined.

Although bimanual interactions (couplings) for diverse hand movements have been of interest, those for bilateral pulling have yet to be examined. Bimanual synchronous behaviors were demonstrated for reaction time during targeting (Marteniuk, MacKenzie, & Baba, 1984; Blinch, Franks, Carpenter, & Chua, 2015) as well as for finger movement (Mechsner, Kerzel, Knoblich, & Prinz, 2001), whereas asynchronous behaviors were observed for the hand force exerted during separate weight lifting (Dimitriou & Buckingham, 2018). Among the three types of bimanual actions used for coordination tasks (discrete, serial, and continuous; Maes, Gooijers, de Xivry, Swinnen, & Boisgontier, 2017), rollable screen unrolling is close to a continuous bimanual action as it involves holding and adjusting the device to determine a preferred screen width. A rollable display device is split into two parts when its screen is unrolled, although these parts are still connected to each other by the screen and the screen support. It is necessary to examine whether bimanual asymmetry in either gripping method or grip design affects the coupling of bimanual grip comfort during bilateral rollable screen pulling.

The objective of the current study was to determine ergonomic rollable display device forms by investigating the main and interactive effects of grip type, device thickness, and hand length on the gripped region of each side bezel and the grip comfort of each hand. Regarding the device forms, we determined the side bezel width and device thickness associated with high grip comfort by considering three grip types (unrestricted grip, restricted grip, and pinch grip), three device thicknesses (2, 6, and 10 mm), and three hand-length groups. In addition, the two hands were compared to determine whether bimanual coupling occurs during screen unrolling with respect to grip widths and grip comfort. Finally, the sizes of the effects of grip type, device thickness, and hand length on grip comfort were compared.

5.2. Material and methods

5.2.1. Participants

Thirty right-handed young individuals (13 male and 17 female) with a mean (standard deviation, SD) age of 22.1 (2.2) years participated in this study. None of the individuals reported any musculoskeletal diseases affecting their upper limbs. Additional efforts were made to obtain three distinctive hand-length groups. This study was approved by a local institutional review board. All of the participants provided written informed consent and were compensated for their time.

5.2.2. Experimental setting

A desk (150 × 60 × 73 cm) and height-adjustable chair were provided. Each of the three prototypes used in this study consisted of acrylonitrile butadiene styrene (ABS) plastic panels, a 0.05-mm-thick paper screen roll (Smartpad, Oxford Corp., South Korea), an ABS plastic screen roller, and a steel spring (to retract the screen). The dimensions of the prototypes used in this study (H × W × R = 140 × 65 × 2.5 mm) followed the recommendations for high one-handed grip comfort and attractive design given by Lee et al. (2018). The thicknesses of the three prototypes were equal on their left sides (T = 10 mm), but different on their right sides (T = 2, 6, and 10 mm; Table 5.1). The 10 mm thickness of the left side was the minimum necessary to house the rolled screen, screen roller, and spring. Regarding the finger position sensing resolution, the just-noticeable differences for the proximal interphalangeal and metacarpal phalangeal joints of the index finger are both approximately 2.5° (Allen & Kleppner, 1992), which is equivalent to a 5 mm flexion or extension of the mean Korean index finger. Considering the shorter length of the thumb, the interval between the device thicknesses was 4 mm, and 2 mm and 6 mm were accordingly considered as the other two device thicknesses. The dimensions of the fully unrolled prototype and screen were H × W = 140 × 290 mm and 120 × 240 mm with aspect ratios (W:H) of 18.5:9 and 18:9, respectively, similar to the screen H:W ratio (2:1) adopted for the latest smartphones (Gil, 2017; Piejko, 2017). When the screen was unrolled, the prototype was equally split into two 32.5-mm-wide sides. The side grip area (bezel) was 20 mm wide. The remaining 25-mm-wide space in the middle partially exposed the rollable screen. To identify the bezel region gripped by each hand, a 1-mm-interval grid image with dimensions of H × W = 130 × 20 mm was attached to each bezel surface (Figure 5.1). The initial force required to unroll the screen should be >2.5 N.

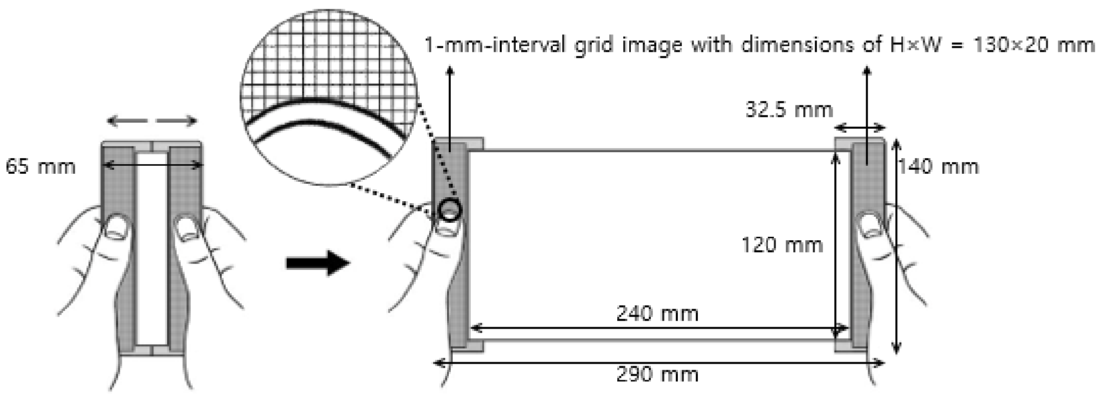
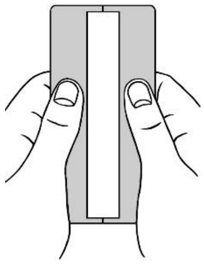
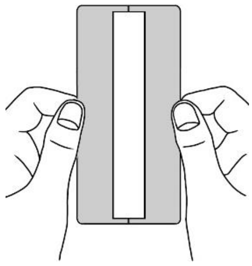
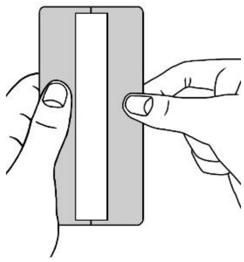
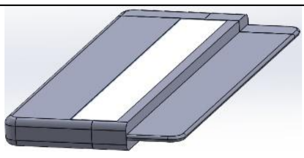
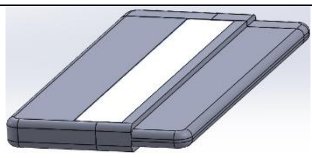
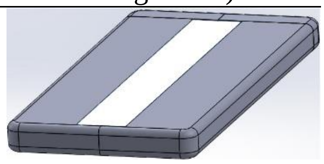


Figure 5.1 Rollable display device prototype with a grid image attached to each bezel to identify the bezel regions involved in gripping (Left: screen retracted, Right: screen fully unrolled).

5.2.3. Experimental design

A 3 (grip type) × 3 (device thickness) × 3 (hand length) mixed factorial design (Table 5.1) was used in the current study. The grip type ($Grip_{FF/MM/FP}$; within-subjects factor), i.e., the gripping method of each hand while unrolling the screen, was a three-level factor and could be designated as $Grip_{FF}$ (gripping both sides of the device freely; unrestricted gripping), $Grip_{MM}$ (gripping both sides of the device minimally; restricted gripping), or $Grip_{FP}$ (gripping the left side freely and pinch-gripping the right side; pinch gripping). The device thickness ($Device_{Thin/Medium/Thick}$; within-subjects factor), i.e., the thickness of the right side of the device, was a three-level factor that could be denoted as $Device_{Thin}$ (2 mm thick), $Device_{Medium}$ (6 mm thick), or $Device_{Thick}$ (10 mm thick). The hand length ($Hand_{S/M/L}$; between-subjects factor) was defined as the distance between the top end of the middle finger and the midpoint interstylon line of the right hand. Based on the right-hand lengths of 20-to-50-year-old South Koreans (SizeKorea, 2015), the hand length was divided into three levels: $Hand_S$ (short hand length; ≤162.5 mm, 10th percentile), $Hand_M$ (medium hand length; 174.6–177.3 mm, 45th–55th percentile), and $Hand_L$ (large hand length; ≥189.4 mm, 90th percentile). These specific percentiles provided differences of at least 12.1 mm between hand-length groups. $Hand_S$, $Hand_M$, and $Hand_L$ consisted of ten female individuals, three male and seven female individuals, and ten male individuals, respectively.

Table 5.1 Three independent variables and their levels

	Level 1	Level 2	Level 3
Grip type (Grip)	 $Grip_{FF}$ (gripping both sides freely)	 $Grip_{MM}$ (gripping both sides minimally)	 $Grip_{FP}$ (gripping the left side freely and pinch-gripping the right side)
Device thickness (Device)	 $Device_{Thin}$ (2 mm thick)	 $Device_{Medium}$ (6 mm thick)	 $Device_{Thick}$ (10 mm thick)
Hand length (Hand)	$Hand_S$ (small hand; ≤162.5 mm; 10th percentile)	$Hand_M$ (medium hand; 174.6–177.3 mm; 45th–55th percentile)	$Hand_L$ (large hand; ≥189.4 mm; 90th percentile)

5.2.4. Experimental procedure and data processing

First, a basic survey was conducted regarding the genders, ages, and musculoskeletal diseases affecting the upper limbs (shoulders, arms, wrists, and hands) of the participants. The length of the right hand of each participant was then measured. The participants familiarized themselves with how to use the prototypes for 5 min. One of nine treatments (3 grip types × 3 device thicknesses) was randomly presented to each participant. With the screen fully unrolled by using the most comfortable grip for the provided treatment, two grip (bezel) regions were each photographed from four different directions. Each individual rated the grip comfort of each hand on a 100 mm visual analogue scale (0: very uncomfortable, 100: very comfortable). A paper-and-pencil method was used for the grip comfort ratings. Each treatment was repeated three times. The total time required for this procedure was about 50 min per participant.

To identify the size of the bezel region gripped by each hand, the left and right bottom corners of the attached grid images were separately used as the origin of an x-y coordinate system (0, 0), with the +x direction being horizontally toward the center of the device and the +y direction being vertically toward the top of the device. The bezel region touched by at least three individuals (or 10%) was considered to be "used for gripping." The grip regions for both hands were manually determined based on the photographs taken for each of the nine treatments. The horizontal and vertical grip widths of each hand were defined as the maximum width and height of the gripped region along the y and x axes, respectively.

5.2.5. Statistical analysis

All of the repeated measures were included in the data analysis. A 3 × 3 × 3 mixed factor analysis of variance (ANOVA) was conducted to examine the main and interaction effects of the grip type, device thickness, and hand length on the horizontal and vertical grip widths and grip comfort for each hand. When a main or interaction effect was significant, a post-hoc pairwise comparison was performed by using Tukey's honestly significant difference (HSD) test. The mean (standard error, SE), 5th, 50th, and 95th percentile values for the horizontal and vertical grip widths were obtained to determine the grip width ranges required to accommodate specific population ratios. The bimanual correlations for the grip widths and grip comfort were analyzed to examine the presence and strength of bimanual coupling. Finally, the partial η^2 values for the three factors (i.e., grip type, device thickness, and hand length) were compared to determine the factor that influenced the grip comfort the most. JMP™ (v12, SAS Institute Inc., NC, USA) was used for all of the statistical analyses. Significance was concluded when $p < 0.05$.

5.3. Results

This section describes the effects of grip type, device thickness, and hand length on the horizontal and vertical grip widths and grip comfort of the rollable display devices. The results of the ANOVA performed on the horizontal and vertical grip widths and grip comfort are summarized in Table 5.2. The gripped regions corresponding to each grip type, device thickness, and hand length are described in Table 5.3, and the mean and percentile values for the horizontal and vertical grip widths according to grip type and device thickness are shown in Figure 5.3. The bivariate correlations depicted in Figure 5.4 explain the bimanual coupling with respect to the horizontal and vertical grip widths and grip comfort for each grip type and device thickness.

5.3.1. Interaction effects

Regarding the horizontal and vertical grip widths for each hand, all of the interaction effects were non-significant ($p \geq 0.084$). For the left-hand grip comfort, all of the interaction effects were non-significant ($p \geq 0.27$) except for grip type × device thickness ($p = 0.022$; Table 5.2 and Figure 5.2). Post-hoc analysis showed that the grip type × device thickness treatments were statistically split into two groups. Five treatments ($Grip_{FF}$ × $Device_{Medium}$, $Grip_{FP}$ × $Device_{Medium}$, $Grip_{FF}$ × $Device_{Thin}$, $Grip_{FP}$ × $Device_{Thin}$, and $Grip_{FP}$ × $Device_{Thick}$) were placed in Group A with $Grip_{FF}$ × $Device_{Thick}$, which provided the highest mean (SE) grip comfort of 80.8 (1.8), whereas two treatments ($Grip_{MM}$ × $Device_{Thin}$ and $Grip_{MM}$ × $Device_{Medium}$) were placed in Group B with $Grip_{MM}$ × $Device_{Thick}$, which yielded the lowest mean (SE) grip comfort of 45.6 (2.8).

Similarly, for the right-hand grip comfort, all of the interaction effects were non-significant ($p \geq 0.14$) except for grip type × device thickness ($p = 0.014$; Table 5.2 and Figure 5.2). The grip type × device thickness treatments were split into three groups ($Grip_{FF}$ × $Device_{Thick}$–$Grip_{FF}$ × $Device_{Medium}$, $Grip_{FF}$ × $Device_{Medium}$–$Grip_{FF}$ × $Device_{Thin}$, and $Grip_{MM}$ × $Device_{Medium}$–$Grip_{FP}$ × $Device_{Medium}$–$Grip_{FP}$ × $Device_{Thick}$–$Grip_{MM}$ × $Device_{Thick}$–$Grip_{MM}$ × $Device_{Thin}$–$Grip_{FP}$ × $Device_{Thin}$). $Grip_{FF}$ × $Device_{Thick}$ showed the highest mean (SE) grip comfort of 80.8 (1.8), and $Grip_{FP}$ × $Device_{Thin}$ yielded the lowest mean (SE) grip comfort of 43.0 (2.8).

Table 5.2 Effects of Grip Type, Device Thickness, and Hand Length on Grip Widths and Grip Comfort

Hand	Measures	Statistics	Grip type (Grip)	Device thickness (Device)	Hand length (Hand)	Grip × Device	Grip × Hand	Device × Hand	Grip × Device × Hand
Left	Horizontal grip width	p	**<0.0001**	0.93	0.94	0.55	0.73	0.084	0.60
		F-ratio	$F_{2, 54} = 123.64$	$F_{2, 54} = 0.068$	$F_{2, 27} = 0.057$	$F_{4, 108} = 0.76$	$F_{4, 54} = 0.51$	$F_{4, 54} = 2.17$	$F_{8, 108} = 0.80$
		Partial η^2	0.821	0.003	0.004	0.027	0.037	0.139	0.056
	Vertical grip width	p	**<0.0001**	0.33	0.90	0.27	0.85	0.92	0.39
		F-ratio	$F_{2, 54} = 14.36$	$F_{2, 54} = 1.13$	$F_{2, 27} = 0.10$	$F_{4, 108} = 1.30$	$F_{4, 54} = 0.34$	$F_{4, 54} = 0.24$	$F_{8, 108} = 1.07$
		Partial η^2	0.347	0.040	0.008	0.046	0.024	0.017	0.073
	Grip comfort	p	**<0.0001**	0.15	0.99	**0.022**	0.38	0.27	0.44
		F-ratio	$F_{2, 54} = 63.79$	$F_{2, 54} = 1.99$	$F_{2, 27} = 0.011$	$F_{4, 108} = 2.98$	$F_{4, 54} = 1.07$	$F_{4, 54} = 1.34$	$F_{8, 108} = 1.01$
		Partial η^2	0.703	0.069	0.001	0.100	0.074	0.091	0.069
Right	Horizontal grip width	p	**<0.0001**	0.072	0.55	0.55	0.99	0.55	0.79
		F-ratio	$F_{2, 54} = 90.99$	$F_{2, 54} = 2.76$	$F_{2, 27} = 0.61$	$F_{4, 108} = 0.77$	$F_{4, 54} = 0.99$	$F_{4, 54} = 0.77$	$F_{8, 108} = 0.58$
		Partial η^2	0.771	0.093	0.044	0.028	0.006	0.054	0.041
	Vertical grip width	p	**<0.0001**	0.56	0.81	0.32	0.78	0.27	0.52
		F-ratio	$F_{2, 54} = 20.14$	$F_{2, 54} = 0.60$	$F_{2, 27} = 0.22$	$F_{4, 108} = 1.18$	$F_{4, 54} = 0.44$	$F_{4, 54} = 1.33$	$F_{8, 108} = 0.90$
		Partial η^2	0.427	0.022	0.016	0.042	0.032	0.090	0.063
	Grip comfort	p	**<0.0001**	**0.0094**	0.55	**0.014**	0.14	0.97	0.52
		F-ratio	$F_{2, 54} = 72.48$	$F_{2, 54} = 5.09$	$F_{2, 27} = 0.60$	$F_{4, 108} = 3.30$	$F_{4, 54} = 1.79$	$F_{4, 54} = 0.13$	$F_{8, 108} = 0.90$
		Partial η^2	0.729	0.159	0.043	0.109	0.117	0.010	0.063

Note. Values of p less than 0.05 are underlined.

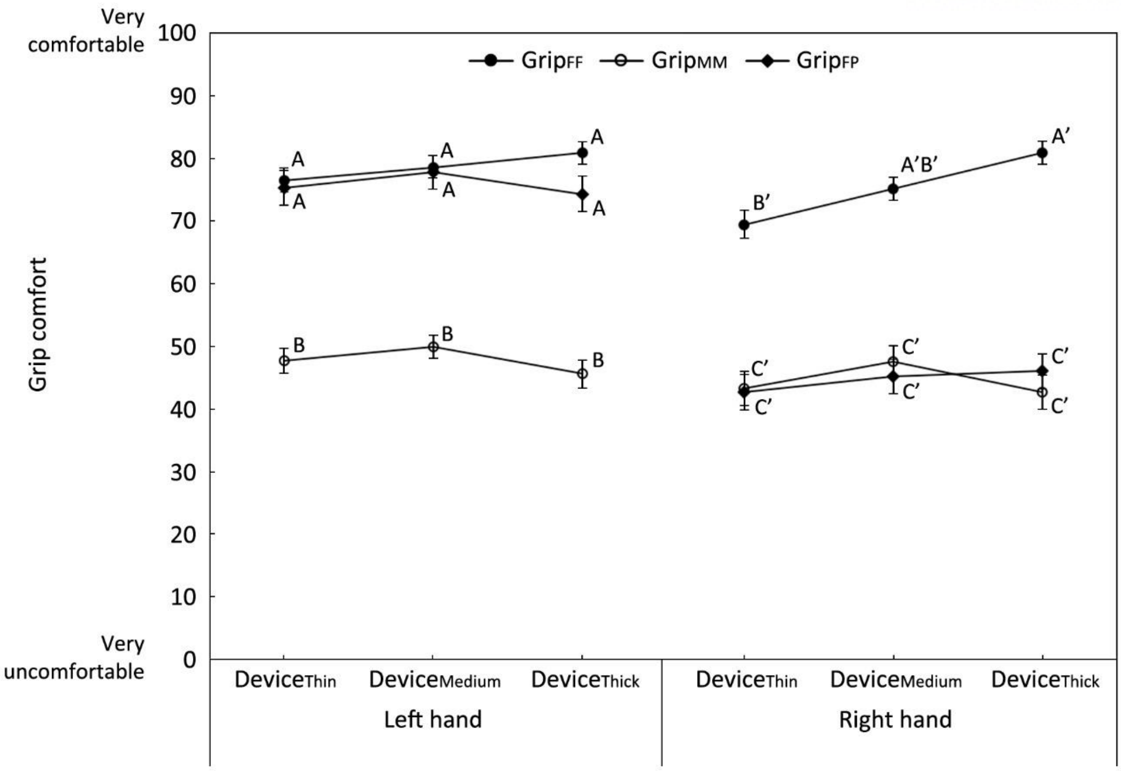


Figure 5.2 Interaction effects of grip type × device thickness on grip comfort for each hand (A and A′: high grip comfort groups for the left and right hands according to Tukey HSD testing; error bars indicate SEs; SE ranges = 1.7–2.8).

5.3.2. Grip type effects

The effects of grip type on both the horizontal and vertical grip widths for the left hand were significant ($p < 0.0001$; Table 5.2; Figure 5.3). Post-hoc analysis of the horizontal grip width for the left hand showed that the grip type levels were statistically split into two groups ($Grip_{FF}$-$Grip_{FP}$ and $Grip_{MM}$). The mean (SD) horizontal grip width of $Grip_{FF}$, 15.7 (4.6), was the widest, and that of $Grip_{MM}$, 8.9 (3.0), was the narrowest. Regarding the vertical grip width for the left hand, the grip type levels were statistically split into two groups ($Grip_{FF}$-$Grip_{FP}$ and $Grip_{MM}$). The mean (SD) vertical grip width of $Grip_{FF}$, 93.5 (20.2), was the widest, and that of $Grip_{MM}$, 83.9 (16.9), was the narrowest.

The effects of grip type on both the horizontal and vertical grip widths for the right hand were significant ($p < 0.0001$; Table 5.2; Figure 5.3). Regarding the horizontal grip width of the right hand, the grip type levels were statistically split into two groups ($Grip_{FF}$ and $Grip_{FP}$-$Grip_{MM}$). The mean (SD) horizontal grip width of $Grip_{FF}$, 15.8 (4.6), was the widest, and that of $Grip_{MM}$, 8.8 (2.7), was the narrowest. Regarding the vertical grip width for the right hand, the grip type levels were statistically split into three groups ($Grip_{FF}$, $Grip_{MM}$, and $Grip_{FP}$). The mean (SD) vertical grip widths corresponding to $Grip_{FF}$, $Grip_{MM}$, and $Grip_{FP}$ were 91.9 (20.8), 82.2 (17.7), and 77.3 (11.3), respectively.

The effects of grip type on grip comfort were significant for both hands ($p < 0.0001$; Table 5.2 and Figure 5.4). For the left-hand grip comfort, the grip type levels were statistically split into two groups ($Grip_{FF}$-$Grip_{FP}$ and $Grip_{MM}$). $Grip_{FF}$ provided the highest mean (SE) grip comfort of 78.6 (1.1), followed by $Grip_{FP}$ (75.8 (1.2)) and $Grip_{MM}$ (47.7 (1.6)). For the right-hand grip comfort, the grip type levels were statistically split into two groups ($Grip_{FF}$ and $Grip_{MM}$-$Grip_{FP}$). $Grip_{FF}$ provided the highest mean (SE) grip comfort of 75.1 (0.8), followed by $Grip_{MM}$ (45.3 (1.1)) and $Grip_{FP}$ (45.2 (1.1)).

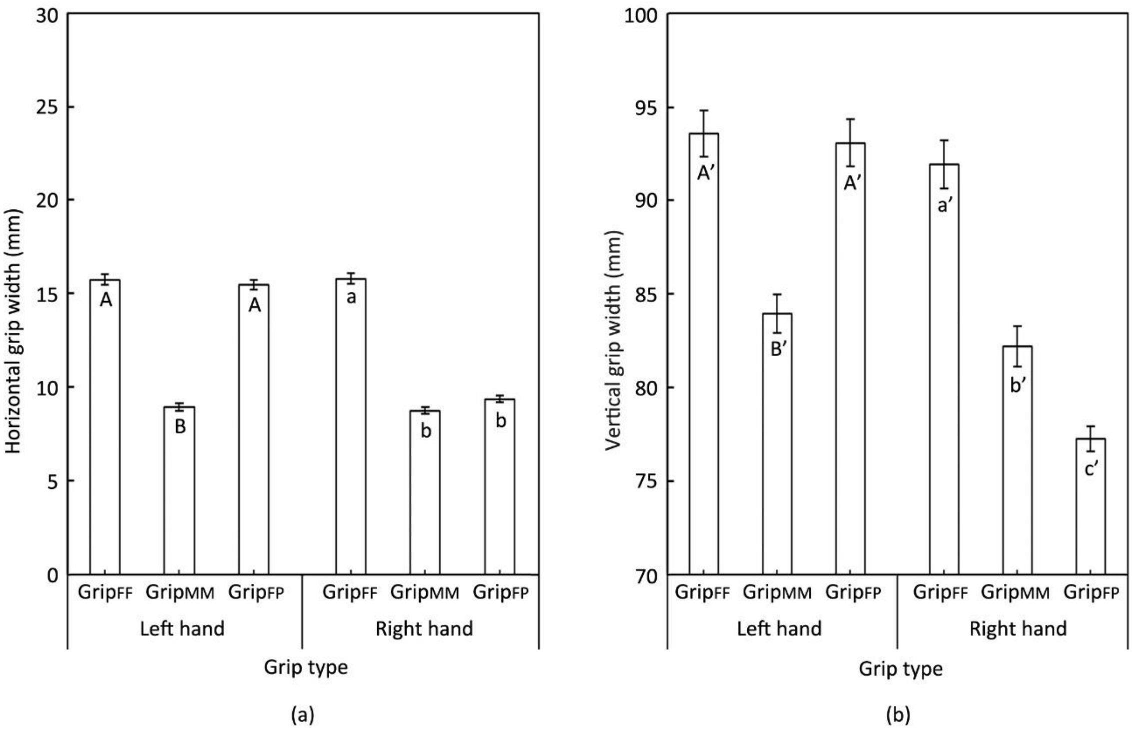


Figure 5.3 Effects of grip type on horizontal and vertical grip widths for each hand (A, A', a, and a': high grip comfort groups for the left and right hands according to Tukey HSD testing; error bars indicate SEs; SE ranges = 0.2–1.3).

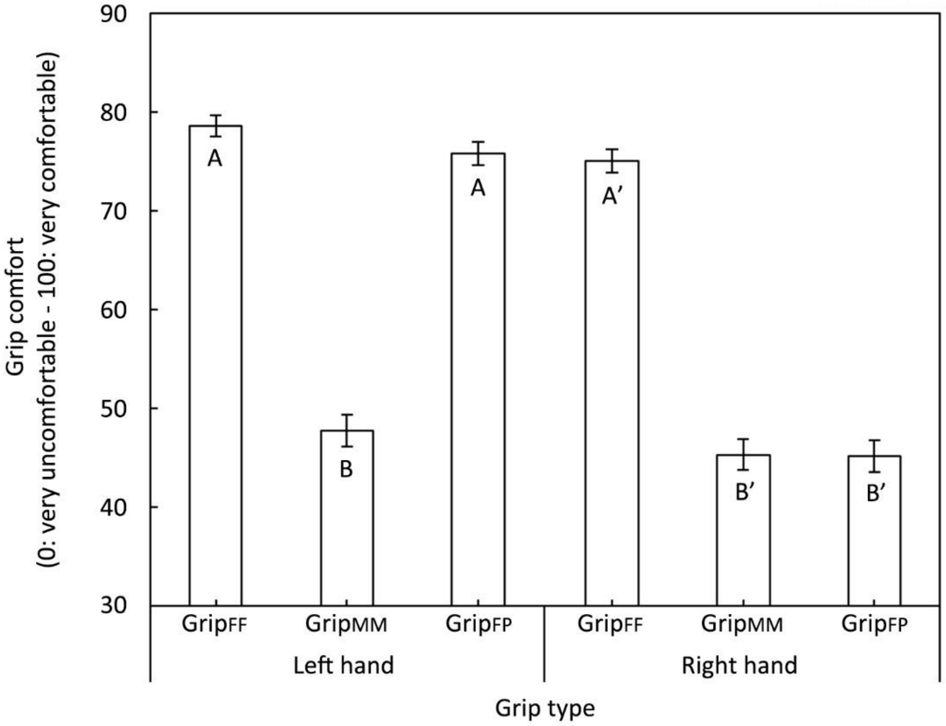


Figure 5.4 Effects of grip type on grip comfort for each hand (A and A′: high grip comfort groups for the left and right hands according to Tukey HSD testing; error bars indicate SEs; SE ranges = 1.1–1.6).

5.3.3. Device thickness effects

The device thickness effects were non-significant ($p \geq 0.072$) for all of the dependent variables except for the right-hand grip comfort ($p = 0.009$; Figure 5.5). The device thickness levels were statistically split into two groups ($Device_{Thick}$-$Device_{Medium}$ and $Device_{Thin}$). $Device_{Thick}$ provided the highest mean (SE) grip comfort of 57.3 (1.2), followed by $Device_{Medium}$ (56.5 (1.1)) and $Device_{Thin}$ (51.7 (1.2)).

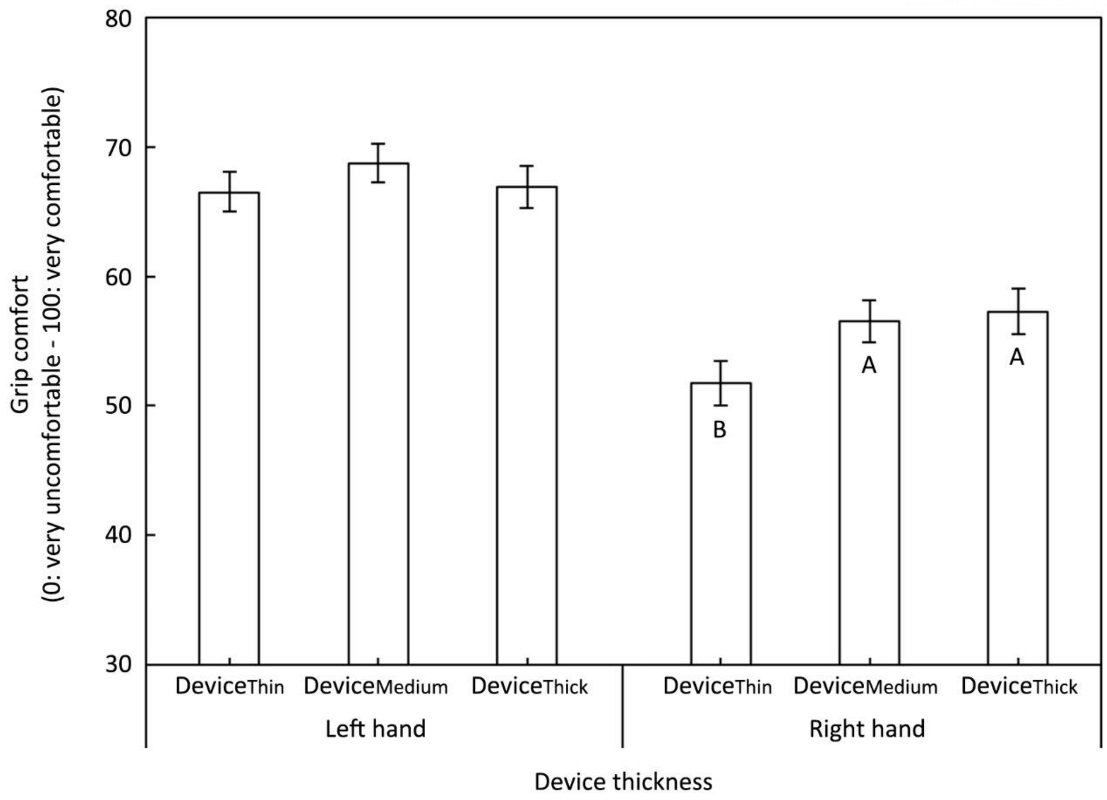


Figure 5.5 Effects of device thickness on grip comfort of each hand (A: high grip comfort group for the right hand according to Tukey HSD testing; error bars indicate SEs; SE ranges = 1.5–1.8).

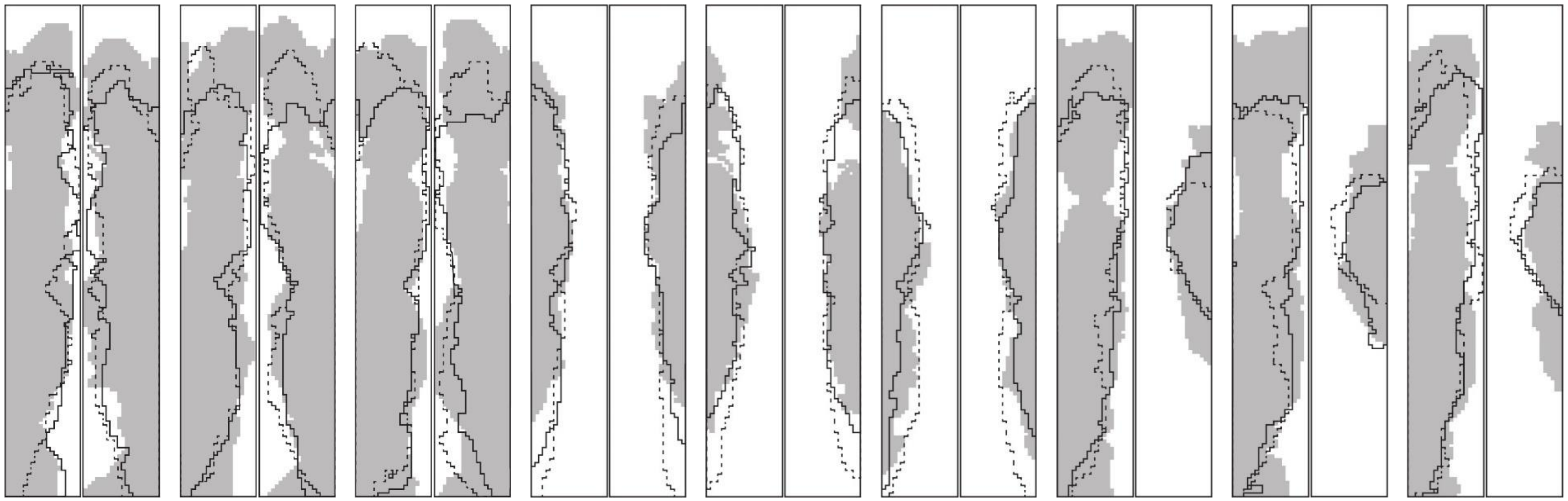
5.3.4. Hand length effects

The hand length effects were non-significant for all six of the dependent variables considered in this study ($p \geq 0.55$; Table 5.2).

5.3.5. Gripped regions and percentile values for grip widths

The bezel regions gripped during screen unrolling with the various grip types, device thicknesses, and hand lengths are summarized in Table 5.3, and the horizontal and vertical grip widths for the mean and 5^{th}, 50^{th}, and 95^{th} percentile values for each grip type are depicted in Figure 5.6. To accommodate 95% of the hand lengths, the width and height of the left (right) bezel should be 20.0 (20.0) mm and 122.6 (123.6) mm for $Grip_{FF}$, 14.0 (13.0) mm and 113.0 (113.6) mm for $Grip_{MM}$, and 20.0 (14.6) mm and 123.0 (95.6) mm for $Grip_{FP}$, respectively.

Table 5.3 Regions gripped during screen unrolling by Grip type, Device thickness, and Hand length

Grip type	$Grip_{FF}$						$Grip_{MM}$						$Grip_{FP}$					
Device thickness	Thin		Medium		Thick		Thin		Medium		Thick		Thin		Medium		Thick	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
Gripped region (left/right)																		

Note. Solid line: short hand, dotted line: medium hand, shaded area: large hand. Each side bezel was 140 mm high and 20 mm wide.

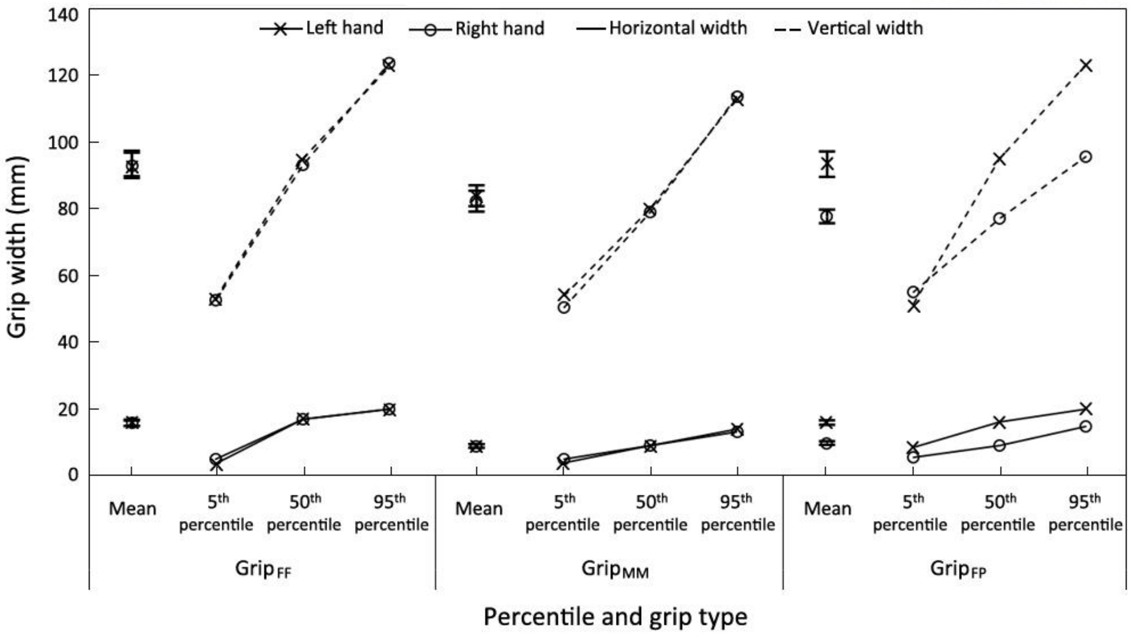


Figure 5.6 Mean and percentile values for the horizontal and vertical grip widths for each grip type (solid lines: horizontal grip widths; dotted lines: vertical grip widths; error bars indicate SEs; SE ranges = 0.49–3.80).

5.3.6. Bimanual coupling with respect to grip widths and comfort

The bimanual coupling strength was analyzed using bimanual correlations for horizontal grip width, vertical grip width, and grip comfort (Figure 5.7). Overall, when both hands were in identical or similar conditions (identical grip types ($Grip_{FF}$ and $Grip_{MM}$) for both hands or identical or similar thicknesses for both device sides), the bimanual correlations for horizontal grip width and grip comfort were high.

In the case of $Grip_{FF}$, the bimanual correlations for the horizontal and vertical grip widths were 0.80–0.86 and 0.82–0.92 ($p \leq 0.0001$), respectively, and those for grip comfort were 0.76–0.97 ($p \leq 0.0001$), for all device thicknesses. In the case of $Grip_{MM}$, the bimanual correlations for the horizontal and vertical grip widths were 0.60–0.86 and 0.89–0.92 ($p \leq 0.0001$), and those for grip comfort were 0.80–0.92 ($p \leq 0.0001$), for all device thicknesses. In the case of $Grip_{FP}$, the bimanual correlations for the horizontal and vertical grip widths were relatively low (0.23–0.30 and 0.53–0.57) for all device thicknesses and were all significant ($p \leq 0.045$), except for the horizontal grip width for $Device_{Thick}$ ($r = 0.13$; $p = 0.20$). Similarly, in the case of $Grip_{FP}$, the bimanual correlations for grip comfort were relatively low (0.22–0.37) for all device thicknesses, although all were significant ($p \leq 0.005$).

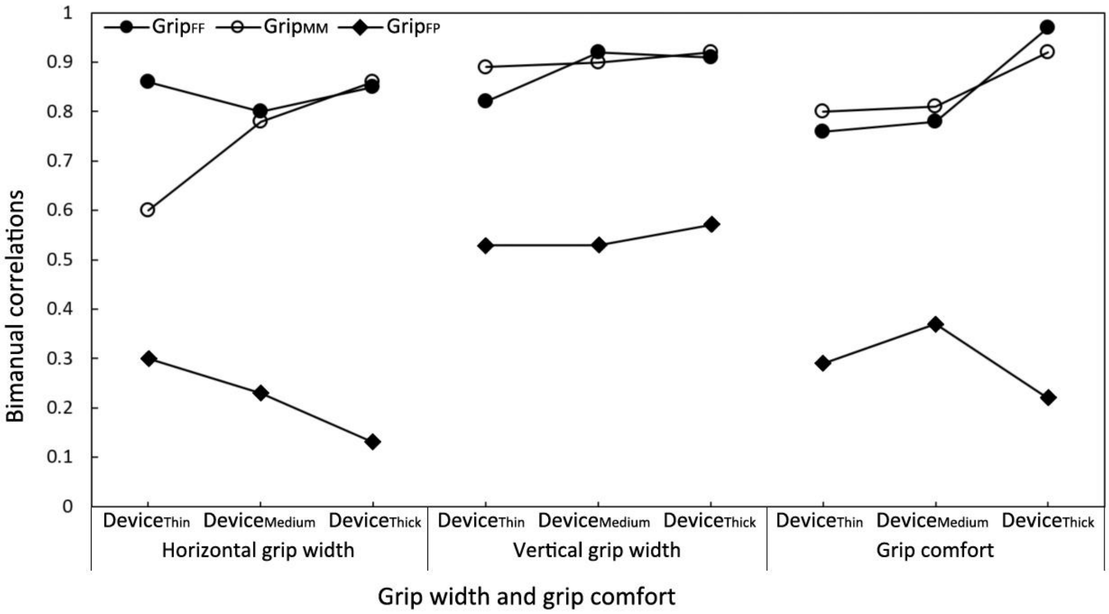


Figure 5.7 Bimanual correlations for the horizontal and vertical grip widths and grip comfort according to device thickness and grip type (all of the bimanual correlations were significant, with $p \leq 0.027$, except for the horizontal grip width for $Grip_{FP}$ × $Device_{Thick}$, with $p = 0.20$).

5.4. Discussions

The effects of grip type, device thickness, and hand length on the horizontal and vertical grip widths and grip comfort associated with screen unrolling were investigated in this study to identify ergonomic grip designs. In this section, the device thickness and grip width requirements are specified, and the grip comfort results of the current study are compared with those of previous studies. In addition, the effects of device thickness and grip type on bimanual coupling with respect to horizontal grip width, vertical grip width, and grip comfort are explained. Finally, the limitations of this study are addressed.

5.4.1. Overview of grip type, device thickness, and hand length effects

Regarding the horizontal and vertical grip widths for both hands, the effect of grip type was significant, whereas the effects of device thickness and hand length were not significant (Table 5.2). For the right-hand grip comfort, the effects of grip type, device thickness, and their interaction were significant. Based on the partial η^2 values, grip type largely accounted for right-hand grip comfort relative to device thickness. Nonetheless, the effects of the device thickness appeared to be non-negligible. Indeed, the interactive effect of grip type × device thickness was significant. For the right hand, $Grip_{FF}$ × $Device_{Thick}$ provided the highest mean (SE) grip comfort of 80.8 (1.8), whereas $Grip_{FP}$ × $Device_{Thin}$ yielded the lowest mean (SE) grip comfort of 42.6 (2.8), and $Grip_{FF}$ × $Device_{Thin}$ was not in the same group as $Grip_{FF}$ × $Device_{Thick}$ (Figure 5.2). Specifically, $Grip_{FF}$–$Device_{Thick}$ (in Group A′) provided the highest mean grip comfort (80.8), followed by $Grip_{FF}$–$Device_{Medium}$ (75.1; in Group A′/B′) and $Grip_{FF}$–$Device_{Thin}$ (69.4; in Group B′), whereas the remaining six treatments provided low grip comfort (≤47.5; in Group C′) (see Figure 5.2). As opposed to grip type and device thickness, hand length did not significantly affect either the grip widths or grip comfort in this study ($p \geq 0.55$).

5.4.2. Grip type effects

Regarding the horizontal and vertical grip widths for both hands, the effect of grip type was significant (see Table 5.2). In the case of $Grip_{FF}$, the 95th percentile horizontal grip widths for both hands were 20 mm, the same as the bezel width of the prototypes. Hence, a bezel width of 20 mm appears to be the minimum necessary to accommodate 95% of individuals. Although the grip comfort for $Grip_{FF}$ was high (75.1), a wider bezel may increase grip comfort further. The 95th percentile vertical grip widths for the left and right hands were 122.6 mm and 123.6 mm, respectively. In the case of $Grip_{MM}$, the 95th percentile horizontal (vertical) grip widths for the left and right hands were 14.0 (113.0) mm and 13.0 (113.6) mm, respectively. In the case of $Grip_{FP}$, the 95th percentile horizontal and vertical grip widths for the right hand were 14.6 mm and 95.6 mm, respectively. The required bezel width for a pinch grip was at least 14.6mm, similar to $Grip_{MM}$ (13–14 mm). Accordingly, when designing rollable devices to accommodate 95% of South Koreans, the horizontal bezel width should be at least 20 mm (around 15 mm for a minimal design concept or for a pinch grip), and the vertical bezel width should be at least 124 mm.

Although the effects of device thickness and grip type were both significant for the right-hand grip comfort ($p \leq 0.0094$), grip type was more influential (partial $\eta^2 = 0.729$ vs. 0.159). The grip type levels were split into two groups ($Grip_{FF}$ and $Grip_{MM}$-$Grip_{FP}$), and the right-hand grip comforts with $Grip_{FF/MM/FP}$ were 75.1/45.3/45.2. Therefore, the horizontal bezel width should be 20 mm rather than 15 mm.

The gripping methods used for rollable display devices are different from those considered in previous studies. Lee et al. (2018) compared the gripping methods used for hand tools requiring high grip force with those for smartphones requiring high grip comfort and operability rather than high grip force and showed that if a degree of firmness is added, the dynamic grip defined by

Kapandji (1983) could better describe smartphone gripping methods than the power, precision, and combined grips defined by Napier (1956). The grip forces with cylindrical handles (Yakou et al., 1997; Kong & Lowe, 2005; Dianat, Nedaei, & Nezami, 2015) or span measuring equipment (Blackwell, Kornatz, & Heath, 1999; Lee, Kong, Lowe, & Song, 2009; Kong, Kim, Lee, & Jung, 2012) involved a power grip, whereas a dynamic grip was used for smart devices (Otten, Karn, & Parsons, 2013; Lee et al., 2016; Lee et al., 2018; Chowdhury & Kanetkar, 2017; Lee et al., submitted). In contrast, rollable screen pulling requires a power that both hands are involved in holding and pulling both sides of the device. After the screen is pulled out, a bimanual dynamic grip (using both hands to grip the device and touch the screen), unimanual power grip (using the other hand only to touch the screen but not to grip the device), or bimanual power grip (using both hands only to grip the device) can be used. The three gripping methods considered in the current study (gripping both sides freely, gripping both sides minimally, and gripping the left side freely and pinch-gripping the right side) were considered for screen unrolling, but not for touch interactions. Hence, the latter may require additional gripping methods. In addition, relatively light prototypes (≤70 g) were used in this study, whereas the means (SEs) for 804 smartphone and 151 tablet PC models from the top five manufacturers are 143.3 (1.03) g and 459.4 (12.0) g, respectively. Holding a display device heavier than a smartphone requires a power grip or firmer dynamic grip rather than the non-firm dynamic grip typically used for smartphone holding.

5.4.3. Device thickness effects

Among the six dependent variables considered in this study, the effect of device thickness was significant only for the right-hand grip comfort ($p = 0.009$; Table 5.2). The right-hand grip comfort increased with increasing device thickness from 51.7 (for $\text{Device}_{\text{Thin}}$), 56.5 (for $\text{Device}_{\text{Medium}}$), to 57.3 (for $\text{Device}_{\text{Thick}}$). $\text{Device}_{\text{Thin}}$ was statistically different from the other two. For the right-hand grip comfort, a device thickness of 6 mm or preferably 10 mm should be used, in addition to a bezel width that accommodates GripFF (a 20 mm width for 95% accommodation).

Mobile objects with a specific range of thicknesses provide high grip comfort. Yakou et al. (1997) showed that the optimum grasping diameter for a cylindrical object was 30–40 mm for men (and 10% lower for women). Kong and Lowe (2005) demonstrated that 41–48 mm and 37–44 mm handle diameters (23.3% of the hand length of the user) maximized the perceived comfort for men and women, respectively. Lee, Kong, Lowe, & Song (2009) investigated a grip span range of 45–55 mm and found that 50–55 mm provided high grip comfort. Kong, Kim, Lee, & Jung (2012) considered a grip span range of 45–55 mm for a custom multi-finger force measuring device and found that the grip feeling changed from comfort to discomfort at 65% of the maximum voluntary contraction for gripping. In addition, the range of cylindrical handle circumferences associated with high grip force and grip comfort, which is 140–151 mm according to Blackwell, Kornatz, & Heath (1999) and Kong and Lowe (2005), includes the perimeter of a smartphone that provides high grip comfort (146 mm; Lee et al., 2018), indicating that the sizes of the grip apertures enclosed by the thumb, palm, and fingers for high grip comfort are similar between circular and rectangular cylinders. When hand-carrying a retracted rollable display device, one-hand grip comfort is important as in non-flexible smartphones. To use the rollable screen, however, both sides of the device should be held and pulled by both hands. Therefore, bimanual grip comfort should be considered.

5.4.4. Bimanual coupling

When identical gripping methods were used for both hands ($Grip_{FF}$ and $Grip_{MM}$), the bimanual coupling with respect to the horizontal and vertical grip widths and grip comfort increased for all three device thicknesses (0.60–0.97 for $Grip_{FF}$ and $Grip_{MM}$ vs. 0.22–0.57 for $Grip_{FP}$; Figure 5.4). In addition, the horizontal and vertical grip widths for $Grip_{FF}$ and $Grip_{MM}$ were similar between the two hands (bimanual differences: 0.0–0.9 mm for horizontal width and 0.2–8.1 mm for vertical width), whereas those for $Grip_{FP}$ were different (bimanual differences across the three hand-length groups: 4.6–6.6 mm for horizontal width and 11.7–22.9 mm for vertical width) (Figure 5.2; Table 5.2).

The interactions between the two brain hemispheres during bimanual symmetric movements contribute to the behavioral coupling between the two arms (Sadato, Yonekura, Waki, Yamada, & Ishii, 1997; Cardoso de Oliveira, Gribova, Donchin, Bergman, & Vaadia, 2001). Therefore, compared with $Grip_{FP}$, the symmetric conditions of $Grip_{FF}$ and $Grip_{MM}$ appeared to cause behavioral coupling during bimanual pulling and to contribute to higher bimanual correlations.

Bimanual actions are divided into three categories (Maes et al., 2017). Discrete bimanual actions are related to tasks that include pauses between movements (e.g., tapping with each hand). Serial bimanual actions are involved in tasks composed of multiple actions in series (e.g., opening the cap of a bottle). Continuous bimanual actions are performed during tasks that are repeated for some time without pausing between repetitions (e.g., drawing a circle with each hand separately but simultaneously). The rollable screen unrolling motion is similar to continuous bimanual action, but the roles and detailed movements of the two hands can be asymmetric. The dominant and non-dominant hands play manipulative and stabilizing roles, respectively (Bagesteiro & Sainburg, 2002; Sainburg, 2002; de Poel, Peper, & Beek, 2007). During a bimanual task, the dominant hand moves first, and the non-dominant hand tends to follow the movement of the dominant hand (de Poel et al., 2007). Hence, asymmetric roles and initial asynchrony of the two hands are expected during bimanual rollable screen pulling, which should be investigated in a future study.

5.4.5. Limitations and future studies

This study had some limitations. First, the force of the spring for screen retraction was always 2.5 N, and the gripping method and grip comfort could change according to the required pulling force (Kong, Kim, Lee, & Jung, 2012; Dianat, Nedaei, & Nezami, 2015). Second, the weights of the three prototype devices were different, with the weights of $\text{Device}_{\text{Thin/Medium/Thick}}$ being 58, 63, and 70 g, respectively. Objects of equal size but different weights can affect grip comfort and preference (Ulin, Armstrong, Snook, & Monroe-Keyserling, 1993; Lee et al., 2018). Furthermore, the mean (SD) weight of 286 smartphone models released by the top five smartphone manufacturers worldwide is 140.5 (37.0) g, and the weight range is 75–500 g. Hence, an additional study using heavier prototypes (≥75 g) is also required. Third, this study was focused on young individuals in their 20s. The hands of older individuals are less sensitive to pressure (Thornbury & Mistretta, 1981), and their muscular strength is weak (Rosenberg, 1997; Rolland et al., 2008). These age-related differences could affect grip comfort. Fourth, the gender ratios differed across the three hand-length groups. Gender-related differences exist in grip force (Nicolay & Walker, 2005; Morse, Jung, Bashford, & Hallbeck, 2006). Because the hand-length effects were all non-significant in the current study, where the Hand_{S} and Hand_{L} groups consisted of 10 women and 10 men, respectively, it is not likely to observe gender-related differences in grip comfort for bilateral screen pulling. Nonetheless, it is worthwhile to examine gender-related differences in grip comfort for bilateral screen pulling using two gender groups with comparable hand sizes. Fifth, all of the participants were right-handed, and the thickness of only the right side of the prototype was varied. Although approximately 73.1-97.5% of the population is right-handed (Llaurens, Raymond & Faurie, 2009), it is necessary to investigate the effects of handedness on bimanual coupling with respect to the grip regions and grip comfort. Sixth, only Koreans participated in this study, although a wide range of hand lengths (150–210 mm or 0.7^{th}–99.9^{th} percentiles) was considered and non-significant hand length effects were observed ($p > 0.55$). Because each ethnic group has distinct hands in terms of size, proportion, shape, and obesity (Davies, Abada, Benson, Courtney, & Minto, 1980; Courtney, 1984), it is necessary to examine whether the findings of the current study can be generalized to different ethnic groups.

Finally, only bimanual screen unrolling on a transverse plane (using the device in landscape mode), but not on a sagittal plane (using the device in portrait mode), was investigated in this study. It is therefore necessary to examine the effects of the screen unrolling direction on the grip regions and grip comfort. Despite these limitations, the fundamental findings of this study will be useful for designing ergonomic rollable display devices.

5.5. Conclusions

The effects of grip type, device thickness, and hand length on the size bezel regions gripped while unrolling the screen of a rollable display device as well as the grip comfort for each hand were investigated in this study to determine ergonomic rollable display device design requirements. The side bezel width necessary to achieve grip comfort was 20 mm across the three investigated hand-length groups. The grip comfort increased as the device thickness increased from 2 mm to 6-10 mm. Hence, a side bezel width of 20 mm and device thickness of 6-10 mm are recommended for rollable display devices. Overall, relative to the device thickness, the grip type greatly influenced the grip comfort and increased the bimanual grip comfort coupling. The hand length effects were not significant for any of the dependent variables. These findings will facilitate the design of ergonomic rollable display devices that provide high grip comfort.

Chapter 6. [Study 5] Future Mobile Display Devices: Rollable Display Devices (Preferred Screen Size)

6.1. Introduction

Some people possess more than one smart device (Anderson, 2015), and they use their devices alternately to suit their different needs (e.g., a small-screen device for texting and a large-screen device for watching videos (Google Inc., 2012). Similarly, in Chapter 4, it was shown that a small screen (140 mm height (H) × 65 mm width (W)) was suitable for calling but was too small for other tasks (e.g., instant messaging, texting, web searching, and gaming), whereas a medium screen (140 H × 130 W) was suitable for gaming and web searching, which implies that a fixed screen size is unable to accommodate diverse user needs and tasks. Unlike current non-flexible (flat or curved) display devices, foldable and rollable display devices are expected to meet diverse user needs (compact size, easy two-hand operation, and large screen; Chapter 4), and rollable displays can be more freely changed in size than foldable ones. However, to the authors' knowledge, there have been no studies on the effect of various sizes of device, task, and hand length on UX, such as preferred screen width, user satisfaction, grip comfort, portability, and design attractiveness.

Over time, the screen aspect ratio of smartphones has been increasing. The first smartphone (iPhone, Apple Inc., USA) had a screen aspect ratio of 3:2 (width: height). After that, most smartphones have offered a screen aspect ratio of 16:9. Since 2017, an 18:9 screen aspect ratio has been adopted by some smartphone models. A rollable display has the advantage of changing the screen aspect ratio by increasing or decreasing the screen length. Therefore, it is expected that UX can be improved by adjusting the screen size for each task with only one device.

The form of smart device can affect the grip comfort, design attractiveness, and gripping method. In a study by Lee et al. (2016), which is related with the smartphone rear interaction, the grip comfort was higher with a 60 mm-width than with a 90 mm-width. In addition, while two gripping methods were predominantly used when touching the front screen, 96.7% of subjects used the same gripping method on the back of the smartphone. Study 4 (Chapter 5) showed that grip comfort increased as the rollable display device thickness increased from 2 mm to 10 mm. Lee et al. (2018) recommended smartphone dimensions of 140 H × 65 (or 70) W × 8 mm thickness (T) × 2.5 mm edge roundness (R) and a mass of 122 g to ensure high one-handed grip comfort and design attractiveness. Also, Lee et al. insisted that smartphone grips can be well explained by the dynamic grip defined by Kapandji (1982) rather than the power grip/precision grip defined by Napier (1956) (calling: firm dynamic grip vs. other tasks: non-firm dynamic grip). When using a rollable display device, users unroll the device while grasping both its sides (close to a lateral pinch having two virtual fingers (the thumb and other fingers), a type of power grip; Napier, 1956). They hold the device with the screen unrolled and input with one or two thumbs or use a gripping posture to see the screen (less firm dynamic grip). As with non-flexible smartphones, research is required to investigate the effect of device form on grip comfort, design attractiveness, and gripping method.

In addition, the preferred screen size or ratio may vary depending on the task. The frequently performed tasks with the smartphone were found to be instant messaging, calling, web searching, video watching, and gaming (KISDI, 2011, DMC Report, 2013, KISA, 2014, KISDI, 2015, KISDI, 2016, Chaffey, 2018). The frequently performed tasks with the tablet PC, which provides larger screen size than the smartphone, were found to be information activities (e.g., web searching), content consumption (e.g., video watching and reading), social activity (e.g., sending E-mails and blogging), games, and instant messaging, but calling was not included (Park & Burford, 2013; Statista, 2016). In Chapter 4, we investigated the preferred screen size for five tasks (instant messaging, calling, texting, web searching, and gaming) using three foldable display device mock-ups with different screen sizes (height was fixed at 140 mm, and width was varied from one to three times 65 mm). Small screen size was preferred for calling, in consideration of one-handed grip, and a 2-3 times larger screen was preferred during tasks that require information on the screen.

On the one hand, screen size should be at least a certain size because input accuracy decreases as the size of the keys decreases and the space between the keys becomes narrower. On the other hand, the screen cannot be too wide so that two-thumb input can be performed comfortably. In the case of the rollable display device, it has the advantage that users can adjust the screen size as they prefer in consideration of task. To develop and improve the UI/UX of rollable display devices, preferred screen sizes for various tasks should be gathered.

Mobile devices should be designed in consideration of hand anthropometry. Grip posture differs by hand size when gripping objects (Cutkosky, 1989), and pressure sensitivities of the finger/palm increase in the distal direction (Allen & Kleppner, 1992). In Study 1 (Chapter 2) the small-hand group reported a high mean hand discomfort and a high mean percentage maximum voluntary exertion for index finger flexion when compared to the medium- and large-hand groups. In a study by Kong & Lowe (2005), comfortable handle diameters increased with hand length (37.3-39.6 mm, 39.6-42.0 mm, and 42.0-44.3 mm for the small-, medium-, and large-hand groups, respectively). In a study by Xiong and Muraki (2016), older users and users with long thumbs encountered larger unreachable zones in the right and bottom screen areas. Conversely, Yi et al. (2017) investigated the effects of display curvature and hand length on smartphone usability, but the effect of hand length was not significant. In Study 2 (Chapter 3), smartphone size for high one-handed grip comfort was consistent regardless of hand length. In Study 4 (Chapter 5), the effect of hand length on grip comfort was not significant when unrolling the rollable display device (149-205 mm (9th-93rd percentile of Korean hand lengths)). However, that study did not consider the various device sizes that exist, and only an unrolling motion was performed rather than practical tasks using the screen. Therefore, a study is required to investigate the effect of the size of rollable display device, task, and hand length on preferred screen width.

The objective of this study was to investigate the effects of device height, task, and hand length on various user experience elements (preferred screen width, preferred screen aspect ratio, user satisfaction, grip comfort, design attractiveness, and gripping method) when using rollable display devices. Three mock-ups with different heights (70, 140, and 210 mm), three tasks (web searching, video watching, and E-mail composing), and three hand length groups were considered.

6.2. Material and Methods

6.2.1. Participants

A total of 30 right-handed individuals (16 male and 14 female) with a mean (SD) age of 22.9 (2.3) years participated in this study. No participants reported any musculoskeletal diseases in their upper limbs. Additional efforts were made to obtain groups of individuals with a wide range of hand lengths. This study was approved by a local institutional review board. All participants provided an informed consent form and were compensated for their time.

6.2.2. Experimental setting and design

The experiment was conducted at a desk (150×60×73 cm) with a height-adjustable chair. The experimental environments of smartphone usage (Lee et al., 2016) and tablet PC usage (Young et al., 2012) are shown in Figure 6.1. A Kinect (for Windows SDK 2.0, Microsoft Corp., USA) and beam projector (EB-4950WU, Epson Inc., Japan) were connected to a desktop computer with an NVIDIA GTX 1080 GPU (Figure 6.1). The size and tilt angle of the screen were measured in real-time by tracking the position of four infrared markers attached to the mock-up (Figure 6.2).

The custom software, which was made by Kinect and OpenCV for Unity (Enox Software, Corp., Japan) on the Unity software platform (v 5.6.4, Unity Technologies Corp., USA), sent out a calibrated image to the rollable screen. Wizard of Oz (Fraser & Gilbert, 1991, Riek, 2012) was used so that an experimenter observes the task progress of subjects and provides the appropriate output using a remote controller. To gather the grip posture of each device height and task, experiments were video recorded by camcorder.

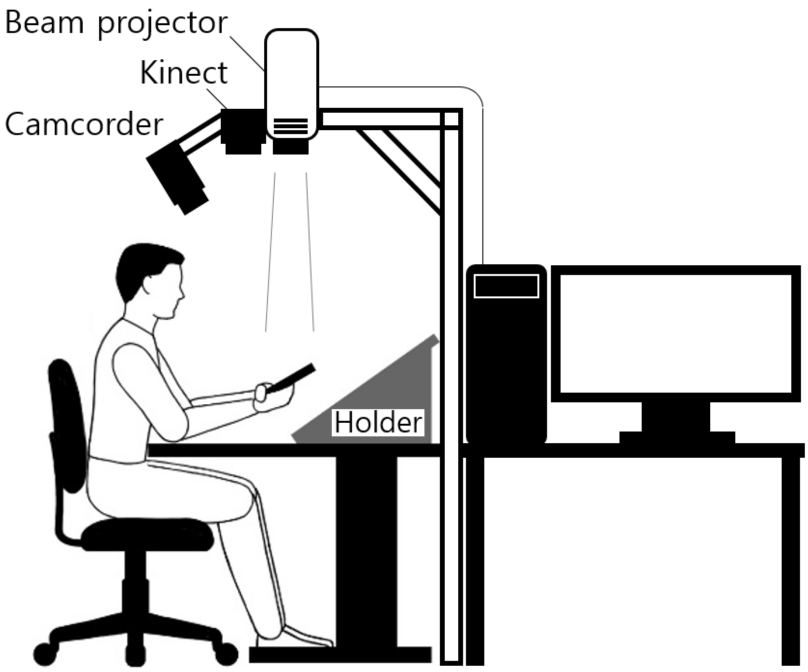


Figure 6.1 Experimental environment.

Each of three rollable display device mock-ups used in this study were comprised of acrylonitrile butadiene styrene (ABS) plastic panels, two rollers, a roll of paper (to show a default screen), and two springs (to roll the screen). The basic size of the rollable mock-up in its fully retracted state was 140 H × 65 W × 10 T × 2.5 R, which is the same as the smartphone size to provide high one-handed grip comfort and design attractiveness; only thickness was changed from 8 T to 10 T for embedding the rollable display. 140 H was defined as medium height, 70 H as short height, and 210 H as tall height. Following the current trend in smartphone screen size (Gil, 2017, Piejko, 2017), the screen aspect ratio (height:width) of the three mock-ups in the fully unrolled state was 1:2 (50 H×100 W, 120 H×240 W, and 190 H×380 W; Figure 6.2).

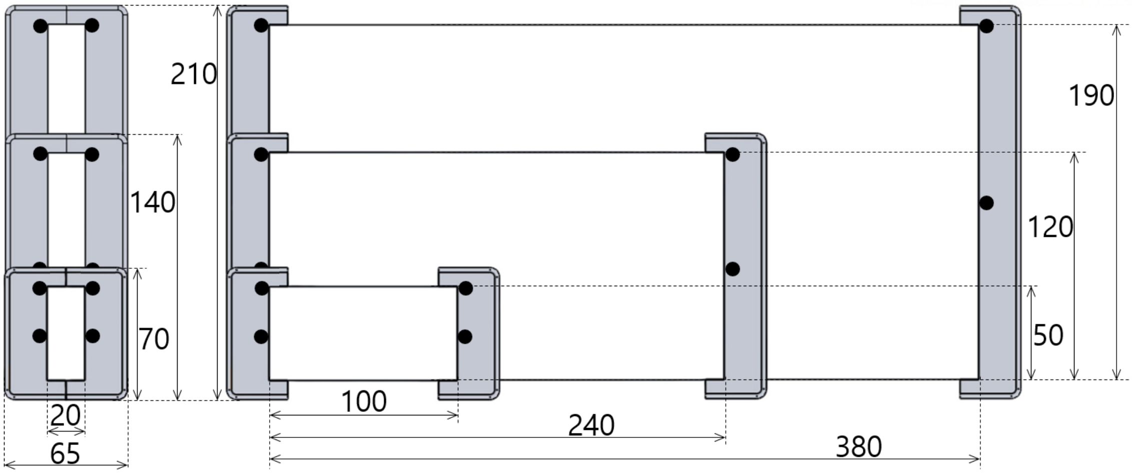


Figure 6.2 Specifications of three mock-ups (unit: mm). Device heights were 70, 140, and 210 mm, and screen heights were 50, 120, and 190 mm, respectively. The screen aspect ratios were all 2:1. The thicknesses of the three mock-ups were all the same at 10 mm. The black circles indicate the infrared markers.

To investigate the effect of device height, task, and hand length on preferred screen width, preferred screen aspect ratio, user satisfaction, grip comfort, portability, design attractiveness, and gripping method for rollable display devices, three independent variables were used. The first independent variable was device height ($Height_{S/M/T}$; within-subjects factor), which contains three levels: $Height_S$ (70 mm), $Height_M$ (140 mm), and $Height_T$ (210 mm). The second independent variable was task (Task; within-subjects factor), which contains three levels: 1) web searching ($Task_{Search}$), 2) video watching ($Task_{Video}$), and 3) E-mail composing ($Task_{Mail}$) (KISDI, 2011, DMC Report, 2013, KISA, 2014, KISDI, 2015, KISDI, 2016, Chaffey, 2018). For $Task_{Search}$, participants read weather information by scrolling down. For $Task_{Video}$, they watched a video for 10 s. For $Task_{Mail}$, they type 'Thank you' and clicked (touched) the send button. The default applications (Internet and Video) of Android were used for $Task_{Search}$ and $Task_{Video}$, and Gmail (Google, LLC., USA) was used for $Task_{Mail}$. The task duration of $Task_{Video}$ was defined based on the study by Fröhlich et al. (2012). Hand length ($Hand_{S/M/L}$), the third independent variable, was divided into three levels: $Hand_S$ (≤162.5 mm, 10th percentile), $Hand_M$ (174.6–177.3 mm, 45th–55th percentile), and $Hand_L$ (≥189.4 mm, 90th percentile). The stated percentile values represent the hand lengths of persons 20–50 years old in the South Korean population (SizeKorea, 2015). These specific percentiles were selected to ensure a minimum difference of 12.1 mm in hand length between groups.

The dependent variables were 1) preferred screen width for each task, 2) preferred screen aspect ratio for each task, 3) user satisfaction associated with performing each task on a screen of preferred size, 4) bi-manual grip comfort for each task, 5) device portability, 6) design attractiveness, and 7) bi-manual gripping method. The preferred screen width was the screen size preferred for each task (mm). Preferred screen aspect ratio was the ratio of preferred screen width to screen height. User satisfaction was the satisfaction of screen size during a simulated task, which was measured by 100-mm VAS (0: very dissatisfied, 100: very satisfied). Grip comfort was the grip comfort for the left- and right-hand during tasks, which was measured by 100-mm VAS (0: very uncomfortable, 100: very comfortable). Device portability was the portability in the totally rolled state, which was measured by 100-mm VAS (0: very poor portability, 100: very good portability). Design attractiveness includes whole factors such attractiveness considering screen size, design, grip comfort, and portability. It was measured by 100-mm VAS (0: very unattractive, 100: very attractive). Gripping methods were categorized in consideration of the hand position based on the video recording.

6.2.3. Experimental procedure

Before the experiment, participant was asked about the purpose and sequence of the experiment for approximately three minutes. Then, participants adjusted the height of the chair for the most comfortable posture. Participants had practice time to become acquainted with the mock-up. Participants gripped the mock-up with both hands and then rolled and unrolled it 10 times. After practice time for all three mock-ups, a one-minute break time was given. After that, 9 mock-ups were randomly given to the participant (three device heights × three tasks). The task window was adjusted to fit the screen in real-time as the screen is unrolled, and participants unrolled the mock-up with the most preferred screen width for the given task. The unrolled preferred screen width was measured using a ruler. Participants answered a user satisfaction questionnaire and stated grip comfort for each given mock-up. If the participant wished, a 35° pedestal was provided for use of a tablet PC (Young et al., 2012; Albin & McLoone, 2014). Between each of the nine mock-ups, a one-minute break was given. After measuring the preferred screen width, user satisfaction, and grip comfort for all mock-ups, portability and design attractiveness for each device were measured. All experiment progress was video recorded to gather gripping methods. The experiment took one hour per participant.

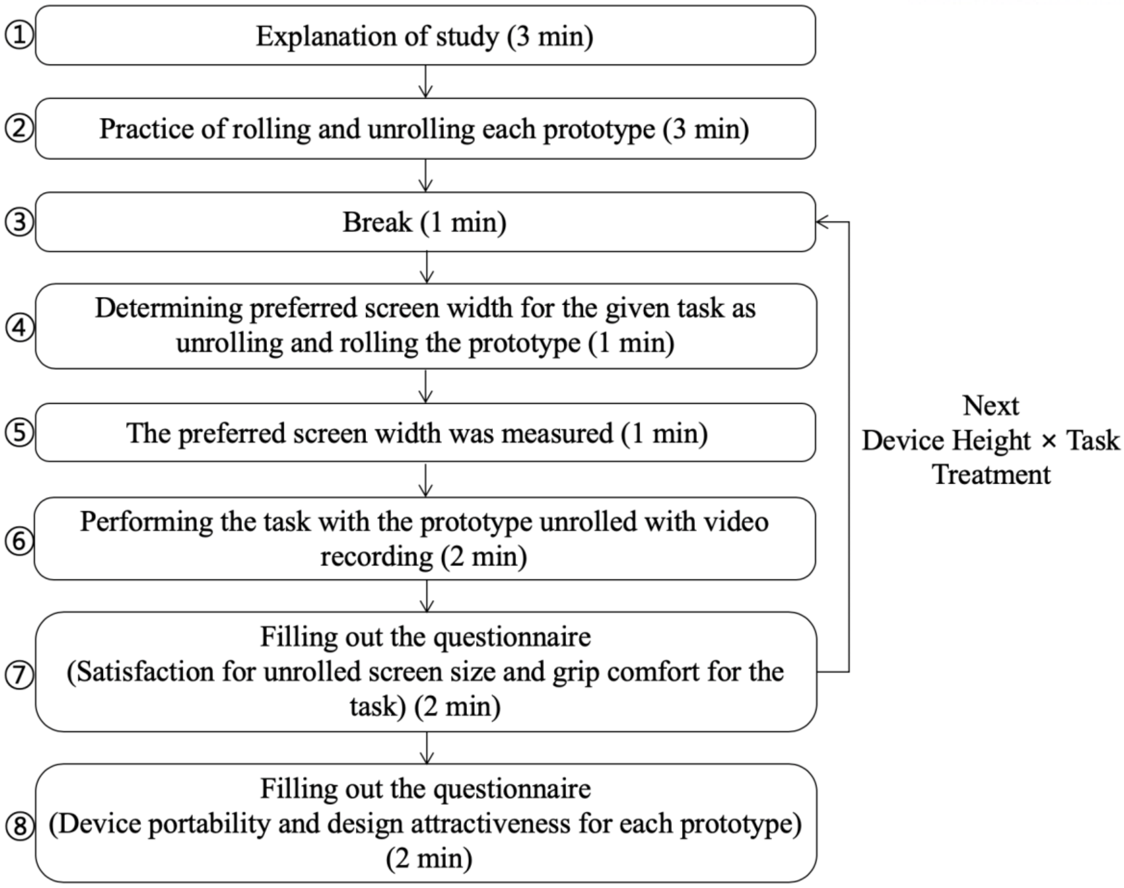


Figure 6.3 Experimental procedure

6.2.4. Statistical analysis

Three-way mixed factor analysis of variance (ANOVA; device height and task: within-subject factors, hand length: between-subjects factor) was conducted for preferred screen width, preferred screen aspect ratio, user satisfaction, and grip comfort. Two-way mixed factor ANOVA (device height: within-subjects factor, hand length: between-subjects factor) was conducted for device portability and design attractiveness. When a main or interaction effect was significant, a post-hoc pairwise comparison was done using Tukey's honestly significant difference (HSD) test. The 95^{th} percentile and range (min-max) of preferred screen width were calculated to define the screen width for each device and task. In addition, screen aspect ratio range was calculated. Finally, the number of gripping methods for each level of device height, task type, and hand length was counted. JMP™ (v12, SAS Institute Inc., NC, USA) was used for all statistical analyses, with significance concluded when $p < 0.05$.

6.3. Results

In this section, the main and interaction effects of three-way (three Height × three Task × three Hand) ANOVA on the preferred screen width, preferred screen aspect ratio, user satisfaction, and grip comfort for each task, and those of 2-way (three Height × three Hand) ANOVA on portability and design attractiveness (for each device) are described (Table 6.1), and the post-hoc tests are explained. In addition, mean (SE), 95th percentile, and range of screen aspect ratio are analyzed.

6.3.1. Device Height × Task effects

Height × Task interaction effect on the preferred screen width was significant (p-value <.0001). A post hoc test showed that Height × Task levels were statistically split into four groups (Figure 6.4). Only $Height_T$ × $Task_{Video}$ was placed in Group A and showed the widest mean (SE) preferred screen width of 247.0 (9.4). Two mock-ups ($Height_S$ × $Task_{Mail}$ and $Height_S$ × $Task_{Video}$) were placed in the same group as $Height_S$ × $Task_{Search}$, which showed the narrowest mean (SE) preferred screen width of 66.9 (3.7).

Height × Task interaction effect on the preferred screen aspect ratio was significant (p-value <.0001). A post hoc test showed that Height × Task levels were statistically split into five groups (Figure 6.5). Four treatments ($Height_S$×$Task_{Video}$, $Height_M$×$Task_{Video}$, $Height_M$×$Task_{Video}$, and $Height_S$×$Task_{Search}$) were placed in the same group as $Height_S$×$Task_{Mail}$, which exhibited the highest mean (SE) preferred screen aspect ratio of 1.5 (0.07). Two treatments ($Height_M$×$Task_{Mail}$ and $Height_T$×$Task_{Mail}$) were placed in the same group as $Height_T$×$Task_{Search}$, which exhibited the lowest mean (SE) preferred screen aspect ratio of 1.0 (0.06). A post-hoc test on preferred screen aspect ratio showed that $Task_{Video}$ belonged to Group A regardless of device height (range of mean aspect ratio: 1.30 – 1.45), and $Height_S$ belonged to Group A regardless of task type (range of mean aspect ratio: 1.34 – 1.46).

Table 6.1 Effects of device height (Height), task type (Task), and hand length (Hand) on preferred screen width, preferred screen aspect ratio, user satisfaction, and grip comfort and effects of device height (Height) and hand length (Hand) on portability and design attractiveness.

		Height	Task	Hand	Height ×Task	Height ×Hand	Task ×Hand	Height ×Task ×Hand
Preferred screen width	p-value	<.0001*	<.0001*	0.023*	<.0001*	0.021*	0.29	0.49
	F Ratio	$F_{2, 54}$ = 291.4	$F_{2, 54}$ = 18.86	$F_{2, 27}$ = 4.35	$F_{4, 108}$ = 11.02	$F_{4, 54}$ = 3.16	$F_{4, 54}$ = 1.28	$F_{8, 108}$ = 0.93
	Partial η^2	0.92	0.41	0.24	0.29	0.19	0.087	0.064
Preferred screen aspect ratio	p-value	<.0001*	<.0001*	0.067	<.0001*	0.37	0.25	0.14
	F Ratio	$F_{2, 54}$ = 23.43	$F_{2, 54}$ = 12.62	$F_{2, 27}$ = 3.00	$F_{4, 108}$ = 8.12	$F_{4, 54}$ = 1.09	$F_{4, 54}$ = 1.39	$F_{8, 108}$ = 1.56
	Partial η^2	0.46	0.32	0.18	0.23	0.07	0.09	0.1
User satisfaction	p-value	<.0001*	0.089	0.21	0.47	0.95	0.95	0.89
	F Ratio	$F_{2, 54}$ = 24.20	$F_{2, 54}$ = 2.53	$F_{2, 27}$ = 1.67	$F_{4, 108}$ = 0.90	$F_{4, 54}$ = 0.18	$F_{4, 54}$ = 0.17	$F_{4, 108}$ = 0.45
	Partial η^2	0.47	0.086	0.11	0.032	0.013	0.012	0.032
Grip comfort	p-value	0.052	0.0052*	0.55	0.41	0.28	0.85	0.34
	F Ratio	$F_{2, 54}$= 3.12	$F_{2, 54}$= 5.81	$F_{2, 27}$= 0.62	$F_{4, 108}$= 1.01	$F_{4, 54}$= 1.30	$F_{4, 54}$= 0.34	$F_{4, 108}$= 1.15
	Partial η^2	0.1	0.18	0.044	0.036	0.088	0.025	0.078
Portability	p-value	0.0014*	-	0.6	-	0.69	-	-
	F Ratio	$F_{2, 54}$= 7.46	-	$F_{2, 27}$= 0.53	-	$F_{4, 54}$= 0.56	-	-
	Partial η^2	0.22	-	0.037	-	0.04	-	-
Design attractiveness	p-value	<0.0001*	-	0.95	-	0.58	-	-
	F Ratio	$F_{2, 54}$= 35.8	-	$F_{2, 27}$= 0.05	-	$F_{4, 54}$= 0.73	-	-
	Partial η^2	0.57	-	0.0037	-	0.051	-	-

*p < .05.

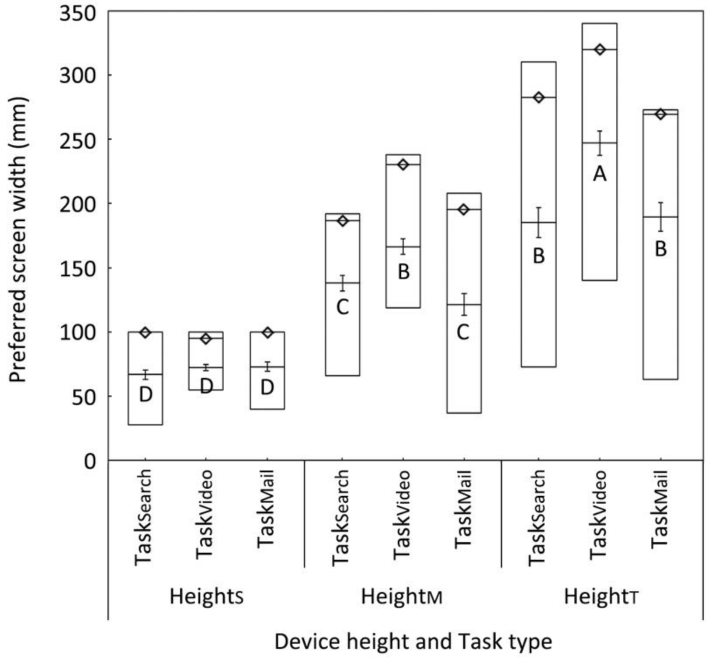


Figure 6.4 Effects of device Height × Task type on preferred screen width (min, mean, 95th percentile (diamond), and max values from the bottom, SE range = 2.5-11.5)

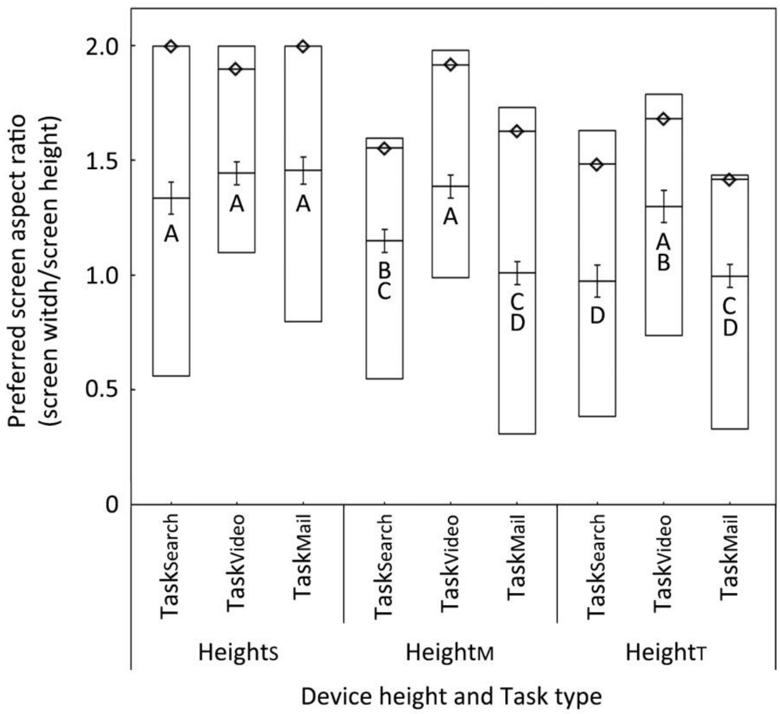


Figure 6.5 Effects of device Height × Task type on preferred screen aspect ratio (min, mean, 95th percentile (diamond), and max values from the bottom; SE range = 0.05-0.07)

6.3.2. Device Height × Hand effects

Height × Hand interaction effect on the preferred screen width was significant (p-values ≤ 0.021). A post hoc test showed that Height × Hand levels were statistically split into five groups (Figure 6.6; Groups A-E). Only $Height_T$ × $Hand_L$ was placed in Group A and showed the widest mean (SE) preferred screen width of 235.5 (11.6).

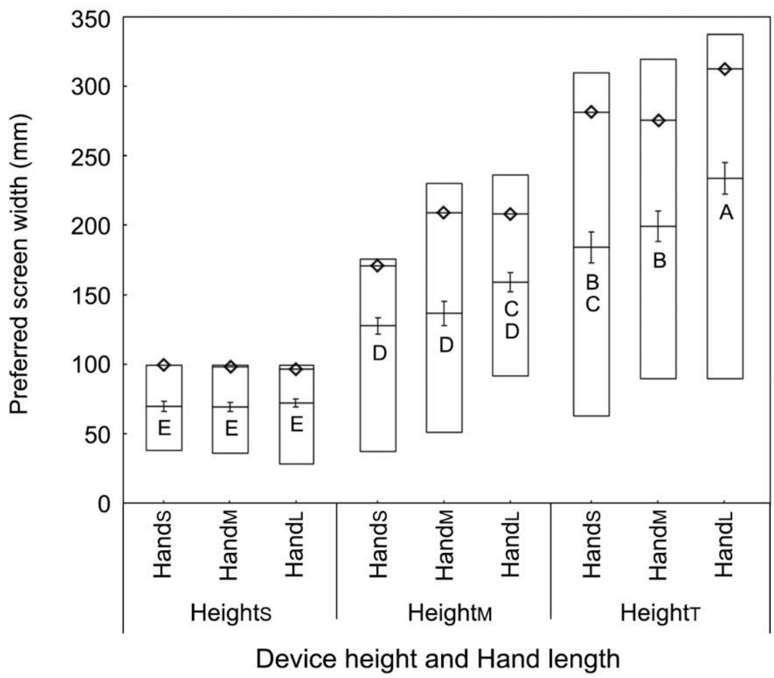


Figure 6.6 Effects of device Height × Hand length on preferred screen width (min, mean, 95th percentile (diamond), and max values from the bottom; SE range = 3.0-11.6)

6.3.3. Device Height effects

The effect of device height on the preferred screen width was significant (p-value <.0001). A post-hoc analysis showed that the three device height levels were statistically different to each other (Figure 6.7). The mean (SE) preferred screen widths of $Height_T$, $Height_M$, and $Height_S$ were 207.2 (6.8), 142.0 (4.4), and 70.7 (1.9), respectively (unit: mm). In consideration of the 95th percentile, the preferred screen widths of $Height_T$, $Height_M$, and $Height_S$ were 311.1, 206.2, and 100.0, respectively (unit: mm). The effect of device height on the preferred screen aspect ratio was also significant (p-value <.0001). A post-hoc analysis showed that only $Height_S$ was in Group A (Figure 6.7), with a mean (SE) of 1.4 (0.04). In consideration of the 95th percentile, an aspect ratio of 2.0 was required only for $Height_S$, and aspect ratios of 1.7 and 1.6 were required for

$Height_M$ and $Height_T$, respectively.

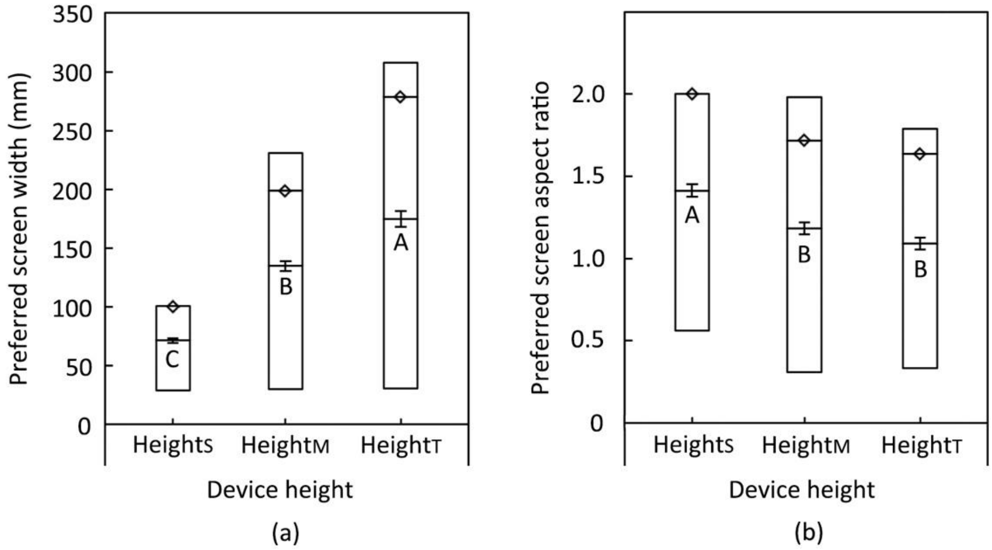


Figure 6.7 Effects of device height on (a) preferred screen width and (b) preferred screen aspect ratio (min, mean, 95th percentile (diamond), and max values from the bottom; SE ranges = 1.9-6.8 and 0.036-0.038).

The effect of device height on the user satisfaction was significant (p-value <.0001). A post-hoc analysis showed that the device height levels were statistically split into two groups (Figure 6.8; $Height_T$-$Height_M$ and $Height_S$). The mean (SE) satisfactions of $Height_T$, $Height_M$, and $Height_S$ were 80.4 (1.6), 78.6 (1.7), and 59.4 (2.8), respectively.

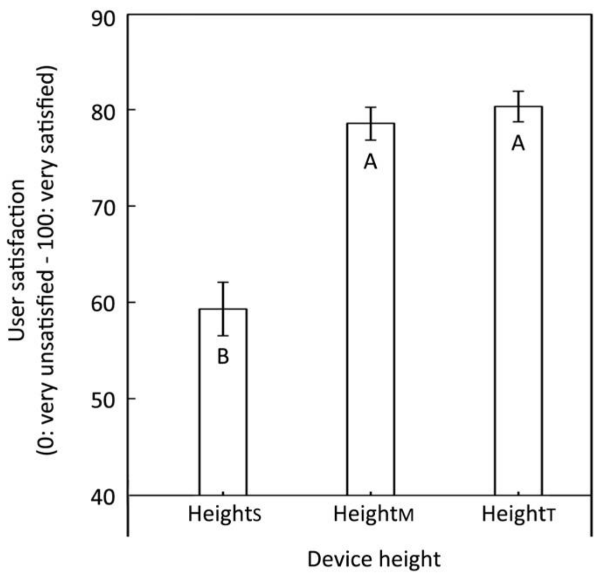


Figure 6.8 Effects of device height on user satisfaction (SE range = 1.3-2.8)

The effects of device height on portability (p-value=0.001) and design attractiveness (p-value <.0001) were significant. Regarding portability, the device height levels were statistically split into two groups (Figure 6.9; Height$_{M}$-Height$_{S}$ and Height$_{S}$-Height$_{T}$). The mean (SE) portability of Height$_{M}$, Height$_{S}$, and Height$_{T}$ were 75.1 (2.6), 67.3 (5.5), and 50.9 (4.7), respectively. Regarding design attractiveness, the device height levels were statistically split into two groups (Figure 6.9; Height$_{M}$-Height$_{T}$ and Height$_{S}$). The mean (SE) design attractiveness of Height$_{M}$, Height$_{T}$, and Height$_{S}$ were 79.3 (2.2), 76.8 (2.8), and 40.3 (4.9), respectively.

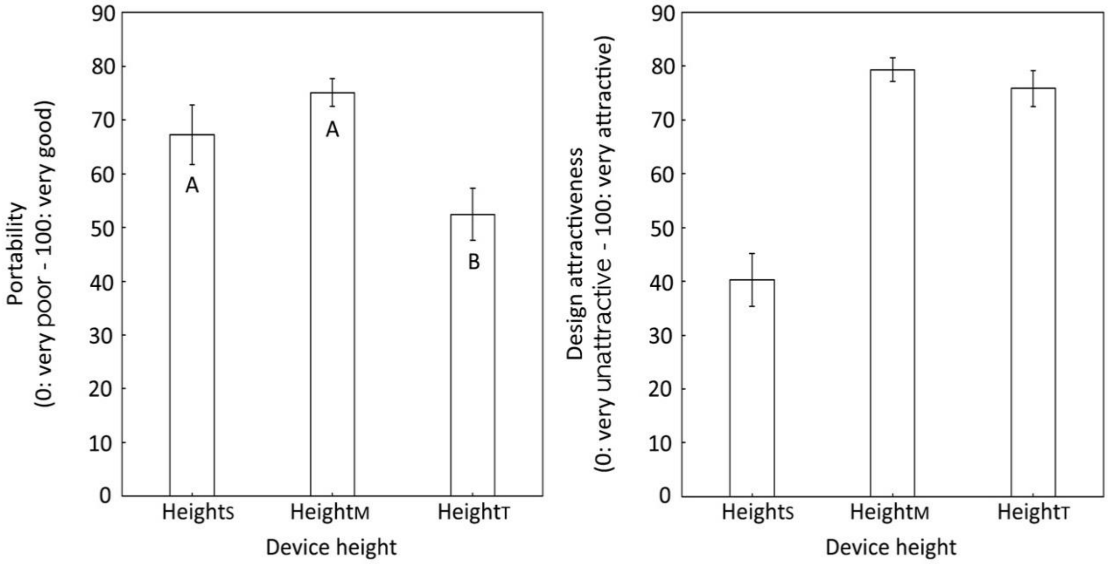


Figure 6.9 Effects of device height on portability and design attractiveness (SE range = 2.1-5.5 for portability and 2.2-4.9 for design attractiveness)

6.3.4. Task type effects

The effect of task type on the preferred screen width was significant (p-value <.0001). A post-hoc analysis showed that the task type levels were statistically split into two groups (Figure 6.10; Task$_{Video}$ and Task$_{Search}$-Task$_{Mail}$). The mean (SE) preferred screen widths of Task$_{Video}$, Task$_{Search}$, and Task$_{Mail}$ were 161.9 (8.4), 130.0 (6.8), and 127.9 (6.9), respectively. The narrowest and widest screen widths were observed with Task$_{Search}$ and Task$_{Video}$, respectively. The mean (SE) preferred screen aspect ratios of Task$_{Video}$, Task$_{Search}$, and Task$_{Mail}$ were 1.4 (0.03), 1.2 (0.04), and 1.2 (0.05), respectively. However, the 95th percentile (SE) preferred screen aspect ratio of Task$_{Video}$, Task$_{Search}$, and Task$_{Mail}$ were 1.8 (0.04), 1.9 (0.03), and 2.0 (0.04), respectively.

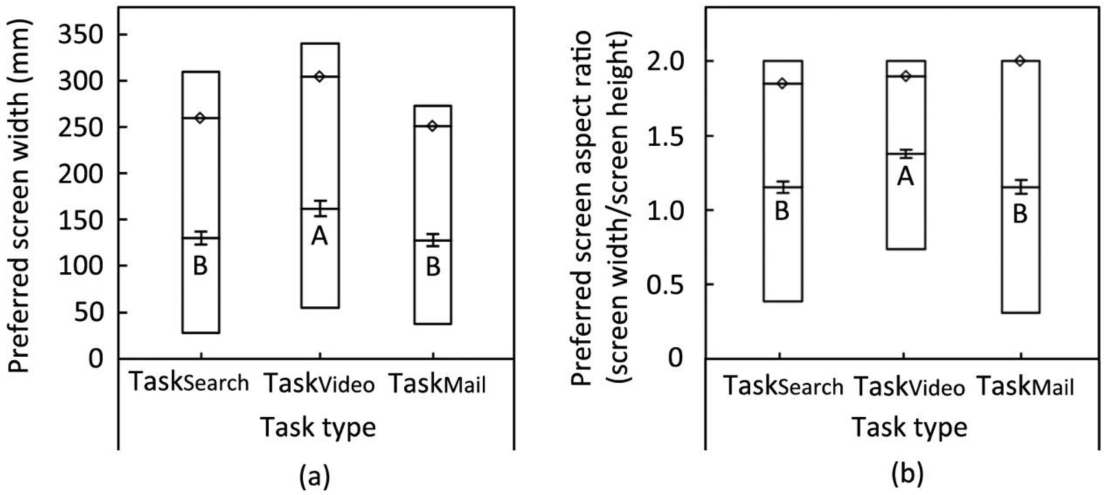


Figure 6.10 Effects of task type on (a) preferred screen width and (b) preferred screen aspect ratio (SE range = 6.8-8.4 for preferred screen width, and 0.03-0.04 for preferred screen aspect ratio).

The effect of task type on grip comfort was significant (p-value=0.004). A post-hoc analysis showed that the task type levels were statistically split into two groups (Figure 6.11; $Task_{Video}$-$Task_{Search}$ and $Task_{Mail}$). The mean (SE) grip comforts of $Task_{Video}$, $Task_{Search}$, and $Task_{Mail}$ were 72.5 (1.9), 71.5 (2.2), and 65.7 (2.2), respectively.

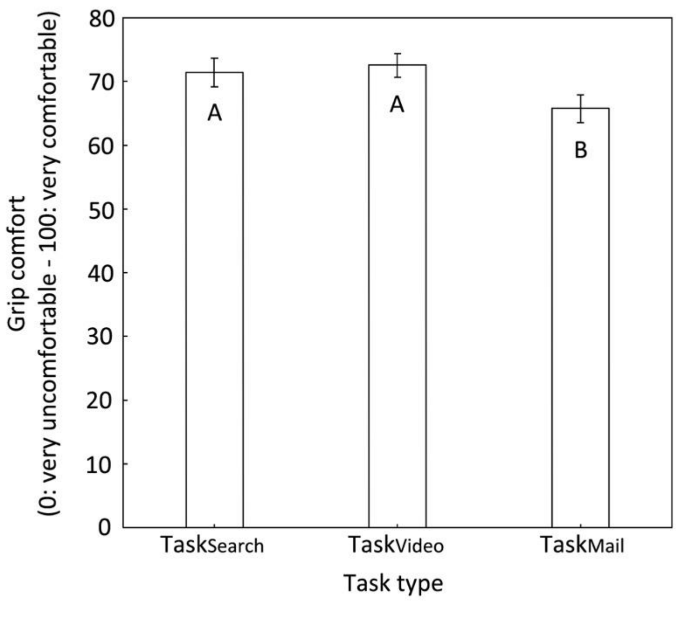


Figure 6.11 Effects of task type on grip comfort (SE range = 1.9-2.2)

6.3.5. Hand length effects

The effect of hand length was significant only for the preferred screen width (p-value = 0.023). A post-hoc analysis showed that the hand length levels were split into two groups (Figure 6.12; $Hand_L$-$Hand_M$ and $Hand_M$-$Hand_S$). The mean (SE) preferred screen widths for $Hand_S$, $Hand_M$, and $Hand_L$ were 127.9 (6.6), 135.9 (7.4), and 156.0 (8.4), respectively. In consideration of the 95th percentile, preferred screen widths (SE) for $Hand_S$, $Hand_M$, and $Hand_L$ were 250.7, 256.7, and 282.5, respectively.

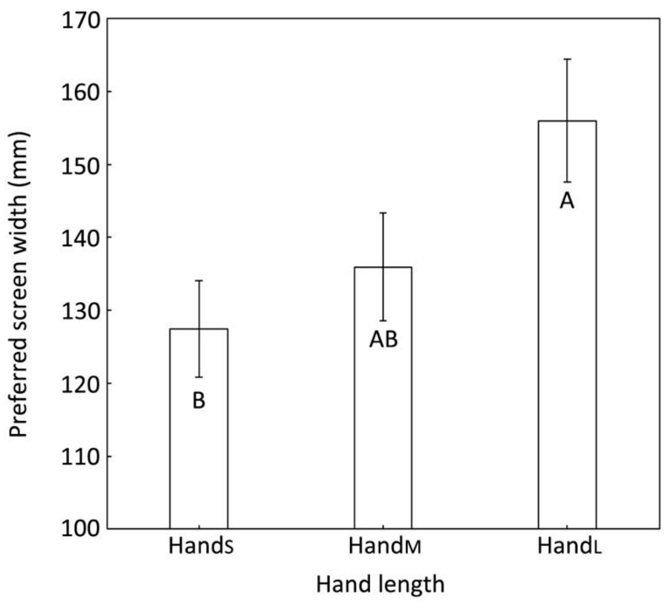


Figure 6.12 Effects of hand length on preferred screen width (SE range = 6.6-8.4)

6.3.6. Gripping methods

Gripping method was categorized into four groups; 1) $Grip_{Both}$ (grip both sides of the device and input with two thumbs), 2) $Grip_{Left}$ (grip left side of the device with left hand and input with right index finger), 3) $Grip_{Lower}$ (hold the bottom of the device and input with right index finger), and 4) $Grip_{No}$ (place the device on the table and input with both hands) (Table 6.2).

Three respective Fisher exact tests between gripping method and each of device height, task type, and hand length were all significant (p-value $\leq$ 0.004). For $Height_S$ and $Height_M$, $Grip_{Both}$ was the predominantly used gripping method (56.7 and 44.4%, respectively). $Grip_{Both}$ was used 38.9% of the time for $Height_T$. As the device height increased, the usage of $Grip_{No}$ also increased (7.2 times increased from 6/90 (6.7%) to 43/90 (47.8%); Figure 6.13). For task type, $Grip_{No}$ was frequently used in order of $Task_{Mail}$, $Task_{Video}$, and $Task_{Search}$ (34/90 (37.8%), 27/90 (30.0%), and

15/90 (16.7%), respectively; Figure 6.13). For hand length, $Grip_{No}$ was frequently used in order of $Hand_S$, $Hand_L$, and $Hand_M$ (35 (38.9%), 24 (26.7%), and 17 (18.9%), respectively; Figure 6.13).

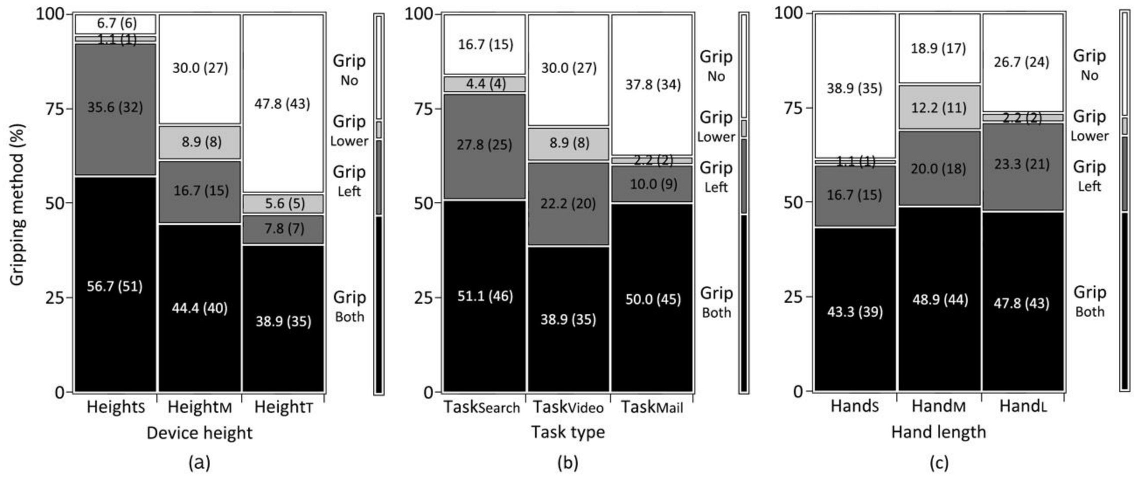
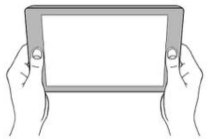
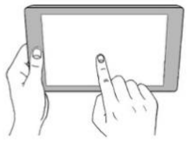
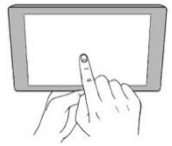


Figure 6.13 Gripping methods by (a) device height, (b) task type, and (c) hand length (numbers within cells are % (number) of participants for each gripping method per device height).

Table 6.2 Gripping method categorization and usage time of each level of Height, Task type, and Hand length.

		Gripping method			
					
		Grip$_{Both}$	Grip$_{Left}$	Grip$_{Lower}$	Grip$_{No}$
		Grip both sides of the device and input with two thumbs	Grip left side of the device with left hand and input with right index finger	Hold the bottom of the device and input with right index finger	Put the device on the table and input with both hands
Device height	Height$_S$	51	32	1	6
	Height$_M$	40	15	8	27
	Height$_T$	35	7	5	43
Task type	Task$_{Search}$	46	25	4	15
	Task$_{Video}$	35	20	8	27
	Task$_{Mail}$	45	9	2	34
Hand length	Hand$_S$	39	15	1	35
	Hand$_M$	44	18	11	17
	Hand$_L$	43	21	2	24

6.4. Discussion

This study examined the effects of device height, task type, and hand length on preferred screen width, preferred screen aspect ratio, user satisfaction, portability, and design attractiveness for rollable display devices to determine ergonomic rollable display device designs. In this section, the results of ANOVA and post-hoc tests are further explained and analyzed. Then, the design guidelines for rollable display devices are provided. Finally, the limitations of this study are addressed.

6.4.1. Overview of effects of device height, task type, and hand length

Among the three independent variables considered in this study (device height, task type, and hand length), device height was most influential on the preferred screen width. Specifically, the effects of device height, task type, and hand length were all significant for the preferred screen width, yet device height (partial $\eta^2 = 0.92$) largely accounted for preferred screen width relative to task type (partial $\eta^2 = 0.41$) or hand length (partial $\eta^2 = 0.24$). Similarly, although the interactive effects of Device height × Task type and Device height × Hand length were significant, their contributions to the preferred screen width were relatively small (partial $\eta^2 = 0.29$ and 0.19; Table 6.1), and these interactive effects could be explained to a large degree by device height alone (See Figures 6.4-6.6). However, task type and hand length also accounted well for preferred screen width based on the partial η^2.

6.4.2. Device height × Task type effects

Regarding the preferred screen width, the Height × Task interaction effect was significant (Figure 6.4). In the results of post-hoc grouping, $Height_S$ showed no significant difference in preferred screen width between tasks, while $Height_M$ and $Height_T$ showed significant differences (preferred screen width was wider for $Task_{Video}$ than that for $Task_{Search}$ and $Task_{Mail}$). When the device height was greater than or equal to $Height_M$, a wider screen was preferred for $Task_{Video}$ than in other tasks.

Regarding the preferred screen aspect ratio, the Height × Task interaction effect was significant (Figure 6.5). In the case of $Height_S$, all three tasks were included in Group A, which describes the highest preferred screen aspect ratio. $Height_M$ × $Task_{Video}$ and $Height_T$ × $Task_{Video}$ were also included in Group A (range = 1.3-1.5). For $Height_{M\text{-}T}$, $Task_{Search}$, and $Task_{Mail}$, preferred screen aspect ratio was 1.0-1.2. The 95th percentiles of the preferred screen aspect ratios for

$Task_{Search/Video/Mail}$ were 2.0/1.9/2.0 for $Height_S$, 1.6/1.9/1.7 for $Height_M$, and 1.6/1.8/1.4 for $Height_T$, respectively. Through these, it can be seen that a screen aspect ratio of 2.0 or larger seems to be needed only for $Height_S$, and an especially larger screen aspect ratio (≥ 1.8) is needed during $Task_{Video}$ over $Task_{Search}$ and $Task_{Mail}$ for $Height_{M-T}$.

6.4.3. Device height × Hand length effects

Height × Hand effect was significant, but most of this result can be explained by the Height effect (except $Height_T$ × $Hand_L$). $Height_T$ × $Hand_L$ was in a different group to $Height_T$ × $Hand_M$ and $Height_T$ × $Hand_S$, and it showed a wider preferred screen width. Thus, participants with large hands preferred the same level of screen width for $Height_S$ and $Height_M$ but preferred a larger screen for $Height_L$. The people with large hands could use a larger device than people with small hands because the people with large hands have a wider thumb range (Xiong & Muraki, 2016).

Across hand lengths and tasks, max (95th percentile) preferred screen aspect ratio ranges for $Height_S$ were 2.0 (1.9-2.0), which was the maximum screen width of a prototype (100 mm, aspect ratio=2.0). Therefore, $Height_S$ appears to be more than an aspect ratio of 2.0. For $Height_M$ and $Height_T$, the max (95th percentile) preferred screen aspect ratio ranges were 1.98 (1.4-1.8) and 1.79 (1.5-1.7), respectively.

6.4.4. Device height effects

The preferred screen width increased with increasing device height (See Figure 6.7), whereas the preferred screen aspect ratio was the highest with $Height_S$, which was grouped differently from the other two levels ($Height_M$ and $Height_T$ were in the same group). Its 95th percentile screen aspect ratio was 2.0, which is the maximum possible value of the prototype. This size is the same as released smartphone models in landscape mode. It is expected that the participants unrolled the mock-up as wide as possible owing to the restriction of screen usage (the amount of information or input). When considering user satisfaction, portability, and design attractiveness, $Height_M$ seems to be the most proper size for a smart device. In the case of user satisfaction, $Height_T$ and $Height_M$ were in the same group (user satisfaction was the highest in $Height_T$), and that was the lowest in $Height_S$ (Figure 6.8). In the case of portability, $Height_M$ and $Height_S$ were in the same group (portability was the highest in $Height_M$), and that was the lowest in $Height_T$ (Figure 6.10). In the case of design attractiveness, $Height_M$ and $Height_T$ were in the same group (design attractiveness was the highest in $Height_M$), and that was the lowest in $Height_S$ (Figure 6.9).

Meanwhile, the ratio of $Grip_{No}$ became higher as the device height increased (ratio of $Grip_{No}$ for $Height_T$ was approximately 7 times higher than that for $Height_S$). As the device size increases, the device becomes heavier and two-thumb reach becomes hard to cover the wide screen width. Therefore, gripping methods such as $Grip_{Lower}$ or $Grip_{Left}$, which are one-handed gripping methods, seem to be inconvenient, and participants seem to place the device on the table to use it.

6.4.5. Task type effects

$Task_{Video}$ was associated with the widest preferred screen width as well as the highest preferred screen aspect ratio. $Task_{Video}$ was the task of watching the video played on the screen without additional input. Among the advantages of the large display mentioned above, a large screen is expected to favor immersion. $Task_{Search}$ is a task of reading articles, and the advantages and disadvantages of large screens coexist. The larger the screen, the more information is provided, but the longer the line, and the lower the legibility (Duchnicky & Kolers, 1983; Sanchez & Wiley., 2009). For $Task_{Mail}$, the screen width is limited by two-thumb reach. For TaskMail, 45/90 (50%) participants used $Grip_{Both}$ among four gripping methods ($Grip_{Both}$, $Grip_{Left}$, $Grip_{Lower}$, and $Grip_{No}$). $Grip_{Both}$ is a dynamic grip with the fingers holding the device and performing additional tasks simultaneously. As mentioned above, unrolling is performed considering two-thumb reach for $Grip_{Both}$. Therefore, it is expected that the preferred screen width is smaller for $Task_{Video}$, which does not have this constraint. For $Task_{Mail}$, grip comfort is also low, which was expected because it involves more input motion than other tasks. Compared to $Task_{Search}$, which has both advantages and disadvantages with a large screen and $Task_{Mail}$, which has limited screen width due to two-thumb reach, $Task_{Video}$ appears to have few disadvantages in terms of large screen because it does not require frequent input.

6.4.6. Hand length effects

Although the preferred screen width was wider as the hand size increased, the preferred screen aspect ratio showed no significant difference between the hand length groups. The larger the hand, the larger the screen, but the difference was not so significant as the change the aspect ratio. The larger the hand length, the longer the thumb length (Xiong & Muraki, 2016), so the thumb reach zone is wider and located at the top when using smartphones (Ahn, Kwon, Bahn, Yun, & Yu, 2016; Kim, Choe, Choi, & Park, 2017; Toh, Coenen, Howie, & Straker, 2017).

6.4.7. Gripping method

The grip posture differed according to the smartphone task. Kim et al. (2006) developed a task prediction model by measuring the grip region when performing eight tasks with a smartphone. Lee et al. (2016) classified the hand posture for the front screen of smartphone usage into three types, and the rear interaction usage into two types based on finger position. However, there are no studies on grip posture when using a tablet PC (the sizes of a typical tablet PC in landscape and portrait modes correspond to $Height_M$ and $Height_T$). Rollable display devices include the concepts of both smartphones and tablet PCs and also can be mid-sized devices, so an integrated grip posture classification that takes these concepts into account is required.

6.4.8. Limitations and future studies

This study had some limitations. First, the viewing duration of $Task_{Video}$ was 10 s. In previous studies, the viewing duration used in display evaluation was very wide, ranging from 10 seconds to four hours (Ardito et al., 1996; Bracken, 2005; Kwon and Lee, 2007; Cho et al., 2010; Fröhlich et al., 2012; Lambooij, Ijsselsteijn, and Heynderickx, 2011; Tam et al., 2011; Lambooij, Ijsselsteijn, and Heynderickx, 2011; Sakamoto et al., 2012; Yand and Chung, 2012; Hou et al., 2012; Zhang, Christou, 2014; liu, et al., 2015; Oh and Lee, 2016). Given that video watching often lasts for a long time, further research on long-term watching is needed. Second, the weights of the three prototype devices were light and different to each other, with the weights of $Height_{Short/Medium/Tall}$ being 35, 70, and 105 g, respectively. The mean (SD) weight of 286 smartphone models released by the top five smartphone manufacturers worldwide is 140.5 g (37.0 g) (Study 4 (Chapter 5)), and the mean (SD) weight of 170 tablet PC models released by the top five tablet PC manufacturers worldwide is 462.5 g (11.1 g). Hence, an additional study using prototypes with heavier weights is also required. Third, the force of the spring for screen retraction was fixed at 2.5 N. The gripping method, grip regions, or grip comfort could change according to the required pulling force (Kong, Kim, Lee, & Jung, 2012; Dianat, Nedaei, & Nezami, 2015; Study 4). Fourth, task performance was not considered. Fifth, it is necessary to investigate proper screen sizes for diverse interaction methods (e.g., pinch zoom or drawing with a stylus pen). Sixth, this study did not consider potential usages of a very wide screen (e.g., viewing very wide panoramic pictures). Seventh, only younger individuals were considered. The preferred screen size of older individuals might be different from that of younger individuals considering the aging factors (e.g., decreased visual acuity). Eighth, only Koreans were considered. Each ethnic group has distinct hand anthropometric dimensions in terms of size, proportion, shape, and weight

(Davies, Abada, Benson, Courtney, & Minto, 1980; Courtney, 1984). Therefore, it is necessary to investigate the effect of different ethnic groups on the preferred screen size of rollable display devices. Finally, the gender ratios differed across the three hand-length groups. Although the mean hand length of males is longer than that of females (Tilley, 2002), it is worthwhile to examine gender-related differences in preferred screen size, preferred screen aspect ratio, user satisfaction, grip comfort, portability, and design attractiveness for rollable display devices using two gender groups with comparable hand sizes. Despite these limitations, the fundamental findings of this study will be useful for designing ergonomic rollable display devices.

6.5. Conclusion

The effects of device height, task, and hand length on various UX elements (preferred screen width, preferred screen aspect ratio, user satisfaction, grip comfort, design attractiveness, and gripping method) when using rollable display devices were investigated in this study to determine ergonomic rollable display device design requirements. Device height largely accounted for preferred screen width relative to task type or hand length. The mean (95^{th} percentile) preferred screen widths of $Height_T$, $Height_M$, and $Height_S$ were 207.2 (100.0), 142.0 (206.2), and 70.7 (311.1), respectively (unit: mm). The mean (95^{th} percentile) preferred screen aspect ratios of $Height_T$, $Height_M$, and $Height_S$ were 1.4 (2.0), 1.2 (1.7), and 1.1(1.6), respectively. $Task_{Video}$ required a wider screen than $Task_{Search}$ and $Task_{Mail}$. The larger the hand length, the larger the preferred screen width. Different display sizes were thus required to accommodate diverse hand lengths and tasks, demonstrating the need for rollable displays, which can easily provide different screen sizes. Among three levels of device height, a device (screen) height of 140 (120) mm with a 142 mm wide screen improved the overall user experience, and 206.2 mm is recommended to accommodate different tasks and diverse user needs in consideration of 95^{th} percentile of preferred screen width. These findings will facilitate the design and UI of ergonomic rollable display devices in terms of screen size preference.

Chapter 7. [Study 6] Future Mobile Display Devices: Rollable Display Devices (Pulling Force)

7.1. Introduction

As mentioned above, concept development and UI studies on foldable and rollable display devices are currently underway, which will be followed by commercialized non-flexible (flat and curved) display devices (Prabhu, 2017, Davies, 2016, Studies 1-6). The rollable display device is expected to solve the problems of small screen size (good portability) and poor portability (large screen), which are the disadvantages of flat and curved display devices. Related to the lateral unrolling of a rollable screen, it is necessary to design the device considering the preferred and acceptable pulling force depending on the thickness of the device and the pulling duration.

External shoulder rotation is required to laterally unroll the rollable display. External shoulder rotation when unrolling is the motion where the upper arm is fixed as a center axis and the hand and lower arm rotate with the shoulder at 0° abduction and elbow flexed to 90° (Reinold et al., 2004). In Study 4 (Chapter 5), the effects of gripping condition, device thickness, and hand length on bimanual grip comfort when using mobile devices with a rollable display were investigated. The results found that grip comfort increased with increasing device thickness, and rollable display devices should have more than 20 mm side bezel widths and 10 mm thicknesses to ensure high grip comfort for bilateral screen pulling. In Study 5 (Chapter 6), the effects of device height, task, and hand length on various user experience elements associated with using rollable display devices (e.g., preferred screen width and grip comfort) were investigated, and a device (screen) height of 140 (120) mm with a 206.2 mm wide screen improved the overall user experience and is recommended to accommodate different tasks and diverse user needs among three levels of device height. In both studies however, the limitation was that pulling force was fixed at 2.5 N. To the authors' knowledge, the user-preferred or acceptable pulling force range for unrolling a rollable screen have never been investigated.

In general, males can apply higher force than females because the muscle size of males is bigger than that of females (Heyward, Johannes-Ellis, & Romer, 1986; Pincivero, Green, Mark & Campy, 2000; Landry, McKean, Hubley-Kozey, Stanish & Deluzio, 2007; Won, Johnson, Punnett & Dennerlein, 2009; Côté, J. N., 2012). In a study by Frontera et al. (1991), the difference of isokinetic strength of the elbow and knee extensors and flexors between genders was considered, and the force of females was 58.7-59.8% of the force of males. To the authors' knowledge however, user-preferred ranges during shoulder external rotation for males and females have never been investigated.

The objective of this study was to investigate the main and interactive effects of gender, device thickness, and pulling duration on pulling forces, muscle activities, and perceived discomfort to determine user-preferred and acceptable screen pulling forces for rollable display devices.

7.2. Materials and methods

7.2.1. Participants

A total of thirty right-handed individuals (1:1 gender ratio) with a mean (SD) age of 22.3 (2.4) years participated in this study. None of the individuals reported any musculoskeletal diseases affecting their upper limbs. This study was approved by a local institutional review board. All of the participants provided written informed consent and were compensated for their time.

7.2.2. Experimental setting

The experiment was conducted at a desk (50×45×65 cm) in a height-adjustable chair. The experimental environment of smartphone usage (Studies 1-5) and tablet PC usage (Young et al., 2012) was used (Figure 7.1). On the table, a digital force gauge (AD4935-50N, Mecmesin Corp., England) was fixed to measure the pulling force, and a mock-up was connected with a hook to the force gauge (Figure 7.1).

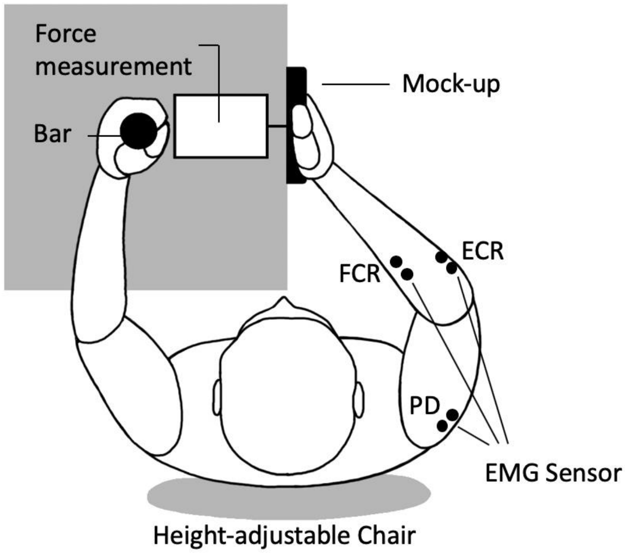


Figure 7.1 Experimental environment. PD, FCR, and ECR indicate posterior deltoid, extensor carpi radialis, and flexor carpi radialis, respectively.

Mock-ups used in this study were comprised of Acrylonitrile Butadiene Styrene (ABS) plastic panels. The size of the mock-ups was defined as 140 H×32.5 W, which referred to the mock-up of Lee et al. (2018) that provides high one-handed grip comfort for calling (140 H×65 W×8 T×2.5 R (mm)), and the width was divided by 2 for separation when unrolling. Device thicknesses of 2, 6, and 10 mm were considered. The weights of each mock-up were 9, 16, and 28 g.

7.2.3. Experimental design

A 2 (gender) × 3 (device thickness) × 3 (pulling duration) mixed factorial design was used in this study. Device thickness (within-subjects factor) was the thickness of the mock-up, which was a three-level factor containing 2 T (2 mm thick), 6 T (6 mm thick), and 10 T (10 mm thick). The level was defined based on Study 4 (Chapter 5). Pulling duration (within-subjects factor) was the duration of pulling the mock-up, which was a three-level factor containing 0.5, 1, and 1.5 s.

Dependent variables were preferred pulling force ($Force_P$), acceptable pulling force ($Force_A$), muscle activity (electromyogram, EMG) when pulling, and perceived comfort when pulling. $Force_P$ and $Force_A$ were measured in a random order. The maximum value of each pulling force (during $Force_P$ or $Force_A$, not the average value) was saved by a digital force gauge. In addition, the muscle activation was measured for the three muscles posterior deltoid (PD), flexor carpi radialis (FCR), and extensor carpi radialis (ECR), which are related to the pulling motion. The PD is the muscle mainly involved in shoulder external rotation (Dark, 2007; Reinold, 2004; Townsend, 1991), and ECR and FCR are the muscles mainly involved in wrist extension and flexion (Gopura, 2010; Ghapanchizadeh, 2015). Muscle activation was calculated as %MVC for comparison. Perceived comfort of right shoulder, upper arm, elbow, lower arm, wrist, and hand when pulling were verbally given using a 7-point scale (1: very uncomfortable, 2: uncomfortable, 3: a little uncomfortable, 4: neutral, 5: a little comfortable, 6: comfortable, 7: very comfortable).

7.2.4. Experimental procedure and data processing

First, participants were informed of the objectives and procedure of this study for five minutes. The experimenter and participant adjusted the chair for neutral posture (back perpendicular to the ground, upper arm fixed as the center axis, hand-lower arm rotates in the shoulder at 0° abduction, and elbow flexed to 90°). The participants were given a mock-up of 140 H x 32.5 W x 10 T x 2.5 R (mm) and had a practice time of three minutes of pulling to become familiar with it. A break time of three minutes was given. In the main experiment, nine treatments (3 device thicknesses ×

3 pulling durations) were randomly given to the participants. The left hand holds the fixed bar, and the right hand holds the mock-up and prepares to pull the mock-up with an external shoulder rotation motion (Figure 7.1). Then, the participant pulled it several times to get an approximate feeling of preferred pulling force and acceptable pulling force. A total of three beep sounds were generated, with a 0.5-s interval between the first and second sounds, and a 0.5, 1, or 1.5 s interval between the second and third depending on the pulling duration being considered; pulling durations were presented in a random order. The participant waits for the first sound. As soon as the second sound is heard, the participant starts pulling the mock-up in the right direction until the third sound is heard. Then, the participant puts the mock-up down on the table and verbally states the perceived comfort of each part of the arm (right shoulder, upper arm, elbow, lower arm, wrist, and hand). After the measurements for the nine treatments are all completed, after a five-minute break, the procedure is repeated once again ($Force_P$ and $Force_A$ are measured twice in each treatment in a random order). The total required time was approximately 80 minutes per participant.

7.2.5. Statistical analysis

A 2×3×3 mixed factor ANOVA was conducted to examine the main and interaction effects of gender, device thickness, and pulling duration on the preferred and acceptable pulling forces, %MVC of three muscles, and perceived comfort of shoulder/upper arm/lower arm/wrist/hand. When a main or interaction effect was significant, a post hoc pairwise comparison was done using Tukey's HSD test. JMP™ (v12, SAS Institute Inc., NC, USA) was used for all statistical analyses. Significance was concluded when $p < 0.05$.

7.3. Results

This section describes the effects of gender, device thickness, and pulling duration on the preferred and acceptable pulling force ($Force_P$ and $Force_A$), %MVC of PD, FCR, and ECR, and perceived comfort (in the shoulder, upper arm, lower arm, wrist, and hand) associated with unrolling a rollable device. The results of the ANOVA performed on the measures are summarized in Tables 7.1 and 7.2.

7.3.1. Interaction effects

Regarding preferred pulling, gender × device thickness interaction effect was significant for

$Force_P$ (p = 0.049) and perceived comfort of the upper arm (p=0.048). For $Force_P$, post-hoc analysis showed that the gender × device treatments were statistically split into three groups. Two treatments (Female × 10 T and Female × 2 T) were placed in Group A with Female × 6 T, which provided the highest mean (SE) $Force_P$ of 6.9 (1.0), whereas Male × 2 T and Male × 6 T were placed in Group B with Male × 10 T, which yielded the lowest mean (SE) $Force_P$ of 5.2 (0.6) (Figure 7.2). For perceived comfort of the upper arm, post-hoc analysis showed that the gender × device thickness treatments were statistically split into three groups (Figure 7.3). Two treatments (Male × 10 T and Male × 2 T) were placed in Group A with Male × 6T, which showed the highest mean (SE) perceived comfort of the upper arm of 5.5 (0.2), whereas Female × 6 T was placed in Group B with Female × 10 T, which yielded the lowest mean (SE) %MVC of ECR of 3.6 (1.3).

Table 7.1 Effects of gender, device height, and pulling duration on preferred pulling force ($Force_P$), %MVC, and perceived comfort associated with unrolling a rollable device

			Gender	Device	Duration	Gender × Device	Gender × Duration	Device × Duration	Gender × Device × Duration
Preferred Pulling Force		p-value	0.325	0.427	0.022*	0.049*	0.710	0.119	0.381
		F-ratio	$F_{1,28}$ = 1.003	$F_{2,56}$ = 0.865	$F_{2,56}$ = 4.066	$F_{2,56}$ = 3.172	$F_{2,56}$ = 0.345	$F_{4,112}$ = 1.882	$F_{4,112}$ = 1.058
		Partial η^2	0.035	0.030	0.127	0.102	0.012	0.063	0.036
%MVC	PD	p-value	0.076	0.201	0.002*	0.475	0.056	0.347	0.602
		F-ratio	$F_{1,28}$ = 3.396	$F_{2,56}$ = 1.654	$F_{2,56}$ = 7.196	$F_{2,56}$ = 0.755	$F_{2,56}$ = 3.029	$F_{4,112}$ = 1.128	$F_{4,112}$ = 0.024
		Partial η^2	0.108	0.056	0.204	0.026	0.098	0.039	0.024
	FCR	p-value	0.484	0.055	0.006*	0.213	0.435	0.095	0.621
		F-ratio	$F_{1,28}$ = 0.504	$F_{2,56}$ = 3.050	$F_{2,56}$ = 5.669	$F_{2,56}$ = 1.589	$F_{2,56}$ = 0.846	$F_{4,112}$ = 2.033	$F_{4,112}$ = 0.660
		Partial η^2	0.018	0.098	0.168	0.054	0.029	0.068	0.023
	ECR	p-value	0.004*	0.003*	<.0001*	0.881	0.011*	0.794	0.413
		F-ratio	$F_{1,28}$ = 9.924	$F_{2,56}$ = 13.028	$F_{2,56}$ = 39.262	$F_{2,56}$ = 0.128	$F_{2,56}$ = 4.871	$F_{4,112}$ = 0.420	$F_{4,112}$ = 0.997
		Partial η^2	0.262	0.318	0.584	0.005	0.148	0.015	0.034
Perceived comfort	Shoulder	p-value	0.002*	0.175	0.013*	0.596	0.450	0.219	0.532
		F-ratio	$F_{1,28}$ = 11.731	$F_{2,56}$ = 1.785	$F_{2,56}$ = 4.702	$F_{2,56}$ = 0.519	$F_{2,56}$ = 0.809	$F_{4,112}$ = 1.460	$F_{4,112}$ = 0.796
		Partial η^2	0.295	0.060	0.144	0.018	0.028	0.050	0.028
	Upper arm	p-value	<.0001*	0.025*	0.235	0.048*	0.974	0.184	0.269
		F-ratio	$F_{1,28}$ = 21.453	$F_{2,56}$ = 3.948	$F_{2,56}$ = 1.485	$F_{2,56}$ = 3.205	$F_{2,56}$ = 0.026	$F_{4,112}$ = 1.584	$F_{4,112}$ = 1.314
		Partial η^2	0.434	0.124	0.050	0.103	0.001	0.054	0.045
	Lower arm	p-value	0.022*	0.463	0.011*	0.110	0.655	0.527	0.261
		F-ratio	$F_{1,28}$ = 5.865	$F_{2,56}$ = 0.781	$F_{2,56}$ = 4.881	$F_{2,56}$ = 2.295	$F_{2,56}$ = 0.426	$F_{4,112}$ = 0.801	$F_{4,112}$ = 1.337
		Partial η^2	0.173	0.027	0.148	0.076	0.015	0.028	0.046
	Wrist	p-value	0.023*	0.345	0.466	0.537	0.815	0.113	0.470
		F-ratio	$F_{1,28}$ = 5.750	$F_{2,56}$ = 1.083	$F_{2,56}$ = 0.774	$F_{2,56}$ = 0.629	$F_{2,56}$ = 0.205	$F_{4,112}$ = 1.915	$F_{4,112}$ = 0.894
		Partial η^2	0.170	0.037	0.027	0.022	0.007	0.064	0.031
	Hand	p-value	0.013*	0.190	0.851	0.832	0.913	0.667	0.004*
		F-ratio	$F_{1,28}$ = 7.130	$F_{2,56}$ = 1.711	$F_{2,56}$ = 0.161	$F_{2,56}$ = 0.184	$F_{2,56}$ = 0.092	$F_{4,112}$ = 0.597	$F_{4,112}$ = 4.072
		Partial η^2	0.203	0.058	0.006	0.007	0.003	0.021	0.127

******p***-value<.05**

Table 7.2 Effects of gender, device height, and pulling duration on acceptable pulling force ($Force_A$), %MVC, and perceived comfort associated with unrolling a rollable device

			Gender	Device	Duration	Gender × Device	Gender × Duration	Device × Duration	Gender × Device × Duration
Acceptable Pulling Force		p-value	0.297	0.872	0.855	0.122	0.543	0.976	0.765
		F-ratio	$F_{1,28}$ = 1.129	$F_{2,56}$ = 0.137	$F_{2,56}$ = 0.157	$F_{2,56}$ = 2.189	$F_{2,56}$ = 0.618	$F_{4,112}$ = 0.119	$F_{4,112}$ = 0.459
		Partial η^2	0.039	0.005	0.006	0.073	0.022	0.004	0.016
%MVC	PD	p-value	0.155	0.265	<.0001*	0.188	0.518	0.322	0.806
		F-ratio	$F_{1,28}$ = 2.138	$F_{2,56}$ = 1.361	$F_{2,56}$ = 13.221	$F_{2,56}$ = 1.725	$F_{2,56}$ = 0.555	$F_{4,112}$ = 1.183	$F_{4,112}$ = 0.403
		Partial η^2	0.071	0.046	0.321	0.058	0.019	0.041	0.014
	FCR	p-value	0.606	0.017*	0.002*	0.597	0.840	0.311	0.947
		F-ratio	$F_{1,28}$ = 0.272	$F_{2,56}$ = 4.358	$F_{2,56}$ = 7.082	$F_{2,56}$ = 0.521	$F_{2,56}$ = 0.176	$F_{4,112}$ = 1.210	$F_{4,112}$ = 0.182
		Partial η^2	0.010	0.135	0.202	0.018	0.006	0.041	0.006
	ECR	p-value	0.001*	0.009*	<.0001*	0.253	0.005*	0.862	0.909
		F-ratio	$F_{1,28}$ = 15.040	$F_{2,56}$ = 5.143	$F_{2,56}$ = 26.723	$F_{2,56}$ = 1.411	$F_{2,56}$ = 5.937	$F_{4,112}$ = 0.323	$F_{4,112}$ = 0.250
		Partial η^2	0.349	0.155	0.488	0.048	0.175	0.011	0.009
Perceived comfort	Shoulder	p-value	0.001*	0.450	0.152	0.143	0.962	0.841	0.830
		F-ratio	$F_{1,28}$ = 13.385	$F_{2,56}$ = 0.809	$F_{2,56}$ = 1.949	$F_{2,56}$ = 2.017	$F_{2,56}$ = 0.039	$F_{4,112}$ = 0.355	$F_{4,112}$ = 0.370
		Partial η^2	0.323	0.028	0.065	0.067	0.001	0.013	0.013
	Upper arm	p-value	<.0001*	0.177	0.664	0.513	0.195	0.166	0.699
		F-ratio	$F_{1,28}$ = 29.426	$F_{2,56}$ = 1.785	$F_{2,56}$ = 0.413	$F_{2,56}$ = 0.675	$F_{2,56}$ = 1.686	$F_{4,112}$ = 1.654	$F_{4,112}$ = 0.551
		Partial η^2	0.512	0.060	0.015	0.024	0.057	0.056	0.019
	Lower arm	p-value	0.007*	0.740	0.183	0.435	0.279	0.507	0.285
		F-ratio	$F_{1,28}$ = 8.649	$F_{2,56}$ = 0.303	$F_{2,56}$ = 1.751	$F_{2,56}$ = 0.844	$F_{2,56}$ = 1.306	$F_{4,112}$ = 0.833	$F_{4,112}$ = 1.273
		Partial η^2	0.236	0.011	0.059	0.029	0.045	0.029	0.043
	Wrist	p-value	0.002*	0.728	0.083	0.233	0.273	0.060	0.207
		F-ratio	$F_{1,28}$ = 12.067	$F_{2,56}$ = 0.320	$F_{2,56}$ = 2.608	$F_{2,56}$ = 1.494	$F_{2,56}$ = 1.331	$F_{4,112}$ = 2.336	$F_{4,112}$ = 1.499
		Partial η^2	0.301	0.011	0.085	0.051	0.045	0.077	0.051
	Hand	p-value	0.001*	0.703	0.370	0.745	0.622	0.721	0.058
		F-ratio	$F_{1,28}$ = 12.733	$F_{2,56}$ = 0.355	$F_{2,56}$ = 1.012	$F_{2,56}$ = 0.296	$F_{2,56}$ = 0.479	$F_{4,112}$ = 0.520	$F_{4,112}$ = 2.359
		Partial η^2	0.313	0.013	0.035	0.010	0.017	0.018	0.078

******p*-value<.05**

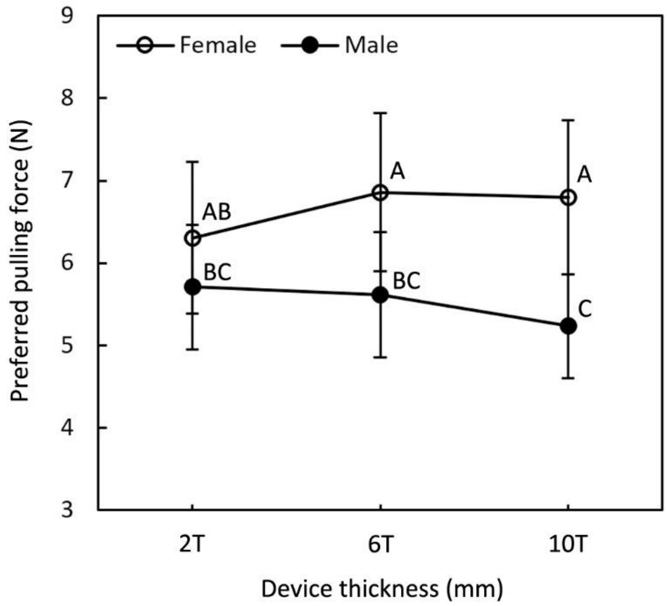


Figure 7.2 Effects of gender and device thickness on Force$_P$ (SE range = 0.6-1.0).

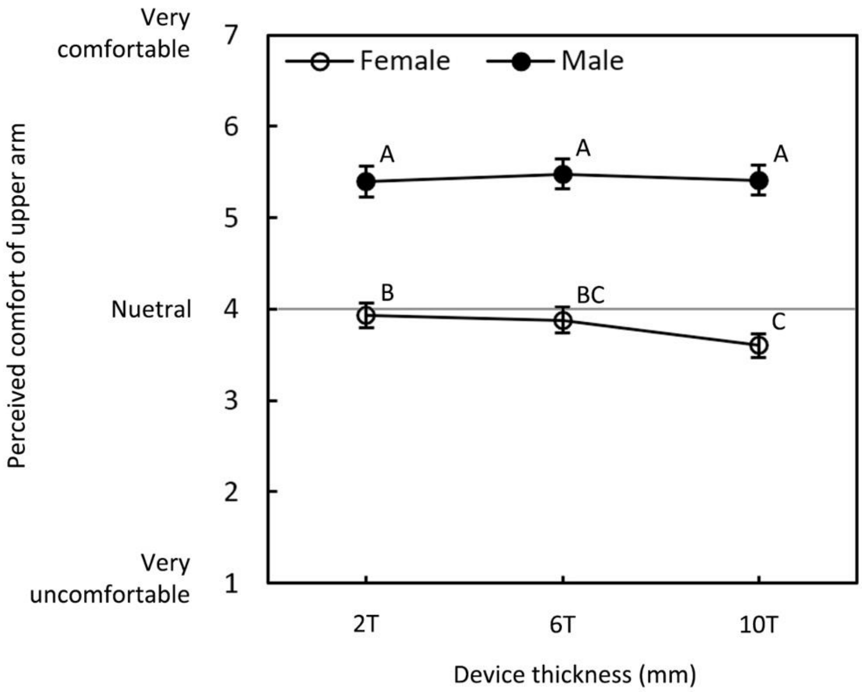


Figure 7.3 Effects of gender and device thickness on perceived comfort of the upper arm associated with preferred pulling (SE range = 0.1-0.2).

Regarding both preferred and acceptable pulling, gender × pulling duration interaction effects on %MVC of ECR were significant (p=0.011 for Force$_P$ and 0.005 for Force$_A$; Table 7.1 and Table 7.2). For Force$_P$, gender × pulling duration treatments were statistically split into two groups (Figure 7.4). Female × 0.5s was placed in Group A with Female × 1 s, which showed the highest mean (SE) %MVC of ECR of 30.6 (2.6), whereas Female × 1.5 s, Male × 0.5 s, and Male × 1 s were placed in Group B with Male × 1.5 s, which yielded the lowest mean (SE) %MVC of ECR of 9.0 (1.4). For Force$_A$, gender × pulling duration treatments were statistically split into three groups. Female × 0.5 s was placed in Group A with Female × 1 s, which showed the highest mean (SE) %MVC of ECR of 49.7 (3.5), whereas Male × 1 s was placed in Group C with Male × 1.5 s, which yielded the lowest mean (SE) %MVC of ECR of 12.7 (1.7).

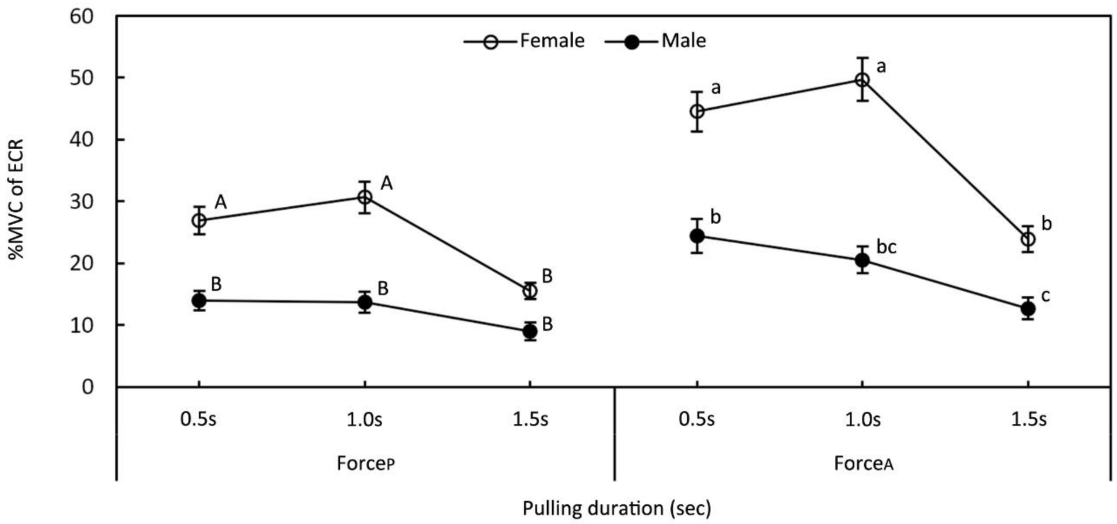


Figure 7.4 Effects of gender and pulling duration on %MVC of ECR (Full name) associated with preferred (ForceP) and acceptable (ForceA) pulling (SE range = 1.3-3.5).

7.3.2. Gender effects

Regarding both preferred and acceptable pulling, the effect of gender on %MVC of ECR was significant (p=0.004 for Force$_P$ and 0.001 for Force$_A$; Table 7.1 and Table 7.2). The result of ANOVA showed that the mean (SE) %MVC of ECR of Female for Force$_P$ was 24.4 (1.3), which was approximately two times larger than that of Male of 12.2 (0.9) (Figure 7.5). The mean (SE) %MVC of ECR of Female for Force$_A$ was 39.4 (2.0), which was approximately two times larger than that of Male of 19.2 (1.4).

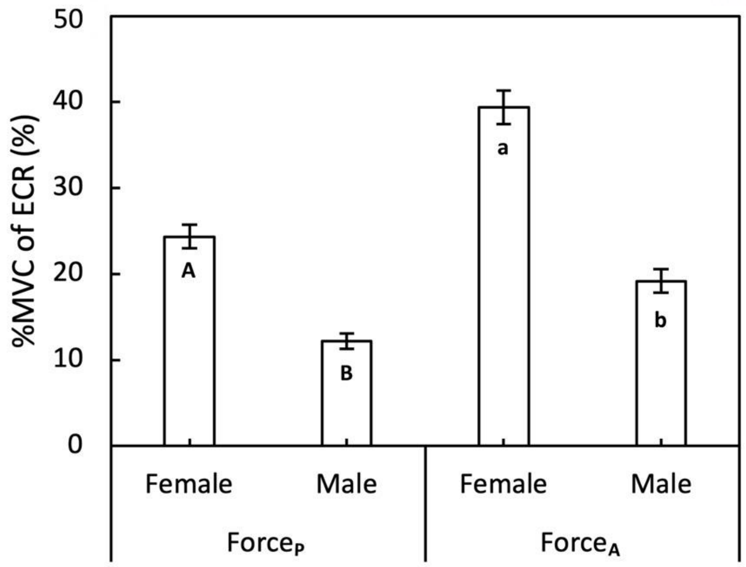


Figure 7.5 Effects of gender on %MVC of ECR associated with preferred ($Force_P$) and acceptable ($Force_A$) pulling (SE range = 0.9-2.0)

Regarding both preferred and acceptable pulling, the effects of gender were significant on the perceived comfort of all four upper limb regions (shoulder, upper arm, lower arm, wrist, and hand) ($p \leq 0.02$; Table 7.1, Table 7.2, and Figure 7.6). Regarding preferred pulling, the perceived comfort of the upper limb was higher for Male (with a range of 4.7-5.5) than for Female (3.6-4.2). Similarly, regarding acceptable pulling, the perceived comfort range of the upper limb was 5.3-6.0 for Male, and that for Female was 4.0-4.5.

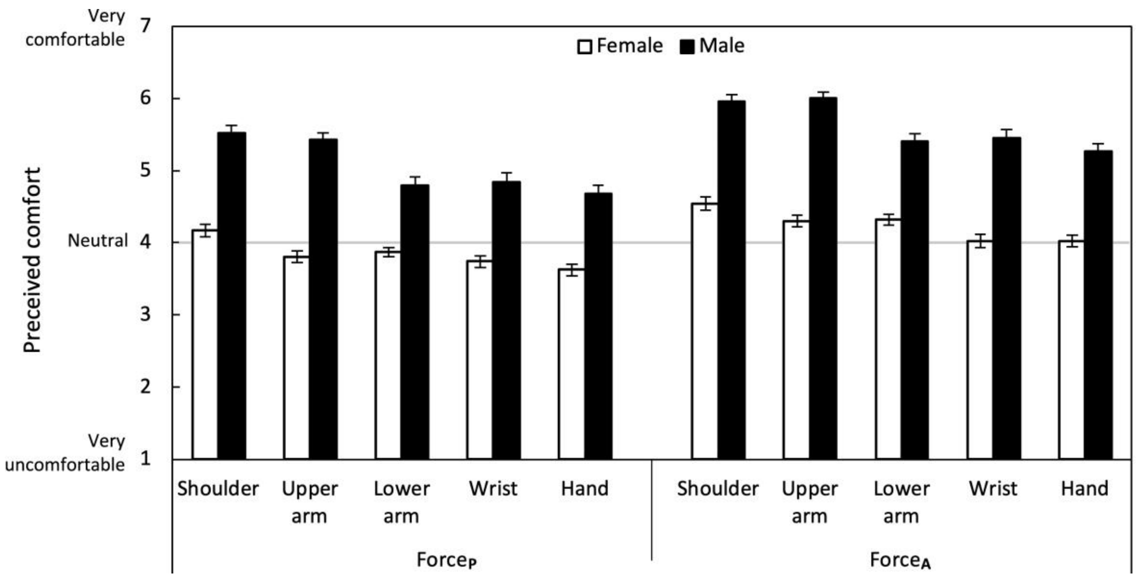


Figure 7.6 Effects of gender on perceived comfort of shoulder, upper arm, lower arm, wrist, and

hand associated with preferred and acceptable pulling (SE range = 0.07-0.14)

7.3.3. Device thickness effects

Regarding acceptable pulling, the effect of device thickness on %MVC of FCR was significant (p=0.017; Table 7.1). Post-hoc analysis showed that the device thickness levels were statistically split into two groups (10 T-6 T and 6 T-2 T; Figure 7.7). The mean (SE) %MVC of FCR for 10 T was the highest at 6.7 (1.1), and that for 2 T was the lowest at 5.0 (0.7).

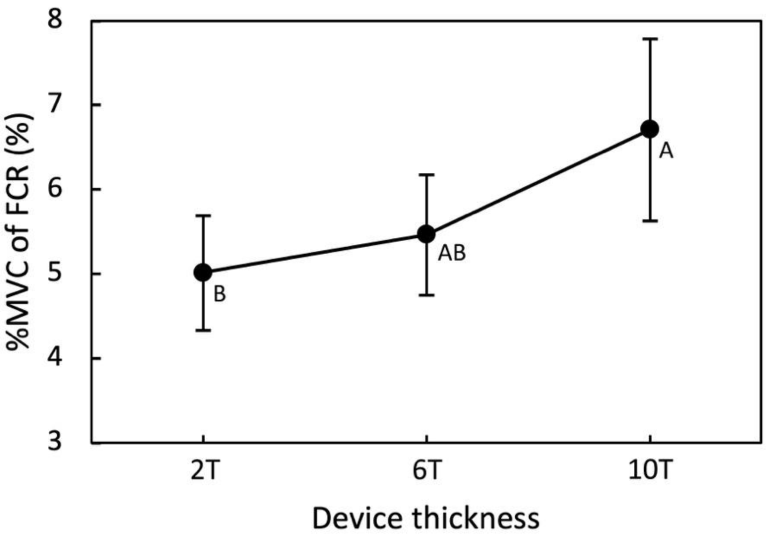


Figure 7.7 Effects of device thickness on %MVC of FCR associated with acceptable pulling (SE range = 0.7-1.1)

Regarding both preferred and acceptable pulling, the effects of device thickness were significant on the %MVC of ECR (p=0.003 and 0.009, respectively; Table 7.1). For %MVC of ECR with $Force_P$, post-hoc analysis showed that the device thickness levels were statistically split into two groups (10 T-6 T and 2 T; Figure 7.8). One treatment (6 T) was placed in Group A with 10 T, which provided the highest mean (SE) %MVC of ECR of 19.2 (1.6), whereas 2 T provided the lowest %MVC of ECR of 16.7 (1.5). Post-hoc analysis of the %MVC of ECR with $Force_A$ showed that the device thickness levels were statistically split into two groups (6 T-10 T and 2 T; Figure 7.8). One treatment (10 T) was placed in Group A with 6 T, which provided the highest mean (SE) %MVC of ECR of 30.6 (2.4), whereas 2 T provided the lowest %MVC of ECR of 26.7 (2.1).

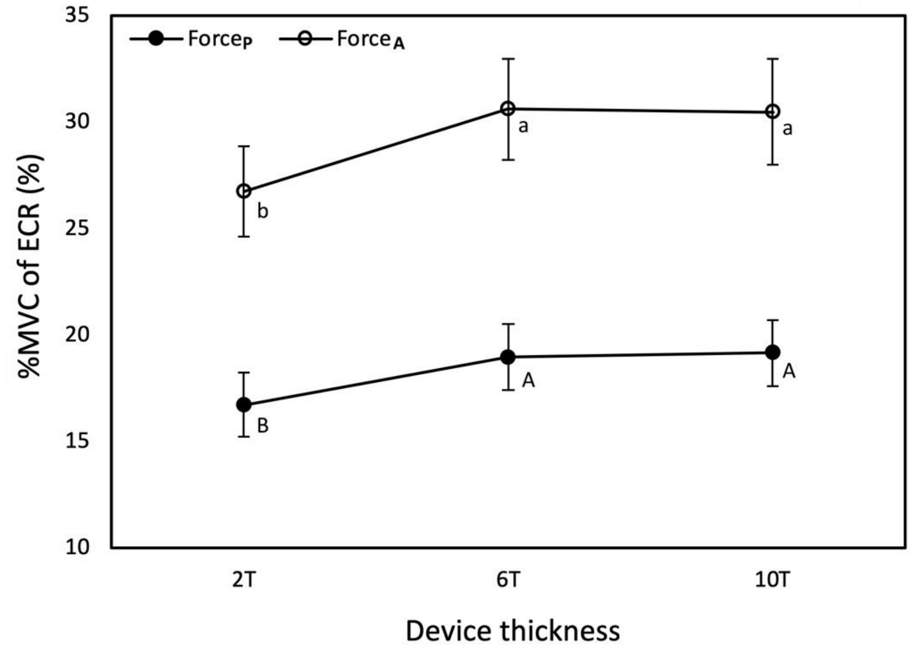


Figure 7.8 Effects of device thickness on %MVC of ECR with Force$_P$ and Force$_A$ (SE range = 1.5-2.5)

For perceived comfort of upper arm, device thickness effect was significant with Force$_P$ ($p=0.025$; Table 7.1). Post-hoc analysis of the perceived comfort of upper arm with Force$_P$ showed that the device thickness levels were statistically split into two groups (6 T-2 T and 2 T-10 T; Figure 7.9). The mean (SE) perceived comfort with 6 T was 4.7 (0.14), which was the highest, and that with 10 T was 4.5 (0.14), which was the lowest.

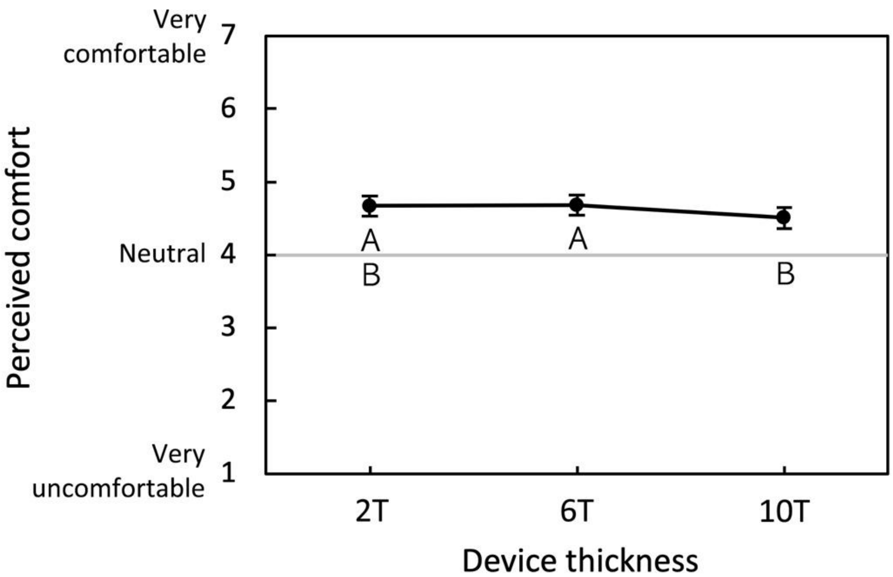


Figure 7.9 Effects of device thickness on perceived comfort of upper arm when pulling with Force$_P$ (SE range = 0.13-0.14)

7.3.4. Pulling duration effects

For $Force_P$, pulling duration effect was significant (p=0.022; Table 7.1). Post-hoc analysis of $Force_P$ showed that the pulling duration levels were statistically split into two groups (1 s-1.5 s and 1.5 s-0.5 s; Figure 7.10). The mean (SE) $Force_P$ with 1 s was 6.3 (0.4), which was the highest, and that with 0.5 s was 5.8 (0.3), which was the lowest.

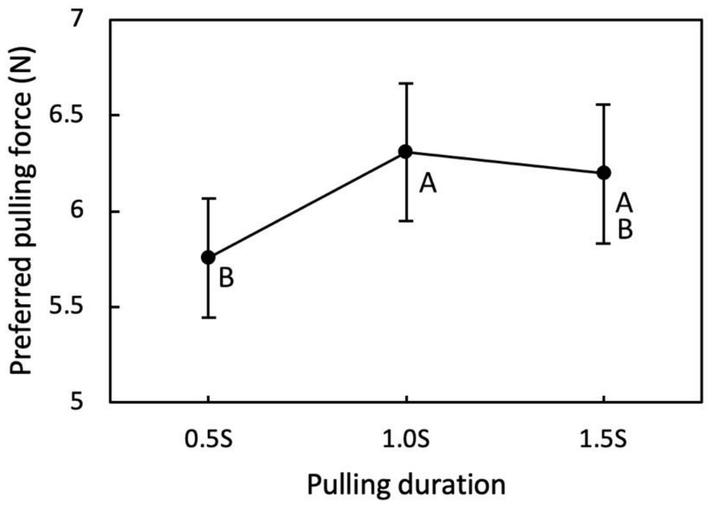


Figure 7.10 Effects of pulling duration on $Force_P$ (SE range = 0.3-0.4)

For %MVC of PD, FCR, and ECR both with $Force_P$ and $Force_A$, pulling duration effects were significant (p<0.006; Table 7.1). For %MVC of PD with $Force_P$, pulling duration was statistically split into two groups (1 s-0.5 s and 1.5 s; Figure 7.11). The mean (SE) %MVC of PD with 1 s was 3.4 (0.4), which was the highest, and that with 1.5 s was 1.9 (0.4), which was the lowest. For %MVC of PD with $Force_A$, pulling duration was statistically split into two groups (0.5 s-1 s and 1.5 s; Figure 7.12). The mean (SE) %MVC of PD with 0.5 s was 7.6 (0.8), which was the highest, and that with 1.5 s was 2.9 (0.6), which was the lowest. For %MVC of FCR with $Force_P$, pulling duration was statistically split into two groups (0.5 s-1 s and 1.5 s; Figure 7.11). The mean (SE) %MVC of FCR with 0.5 s was 3.5 (0.6), which was the highest, and that with 1.5 s was 2.1 (0.3), which was the lowest. For %MVC of FCR with $Force_A$, pulling duration was statistically split into two groups (0.5 s-1 s and 1.5 s; Figure 7.11). The mean (SE) %MVC of FCR with 0.5 s was 6.9 (1.0), which was the highest, and that with 1.5 s was 3.7 (0.4), which was the lowest. For %MVC of ECR with $Force_P$, pulling duration was statistically split into two groups (1 s-0.5 s and 1.5s; Figure 7.11). The mean (SE) %MVC of ECR with 1 s was 22.2 (1.6), which was the highest, and that with 1.5 s was 12.2 (0.9), which was the lowest. For %MVC of ECR with $Force_A$, pulling duration was statistically split into two groups (1 s-0.5 s and 1.5 s; Figure 7.11). The mean

(SE) %MVC of ECR with 1 s was 35.1 (2.4), which was the highest, and that with 1.5 s was 18.3 (1.3), which was the lowest.

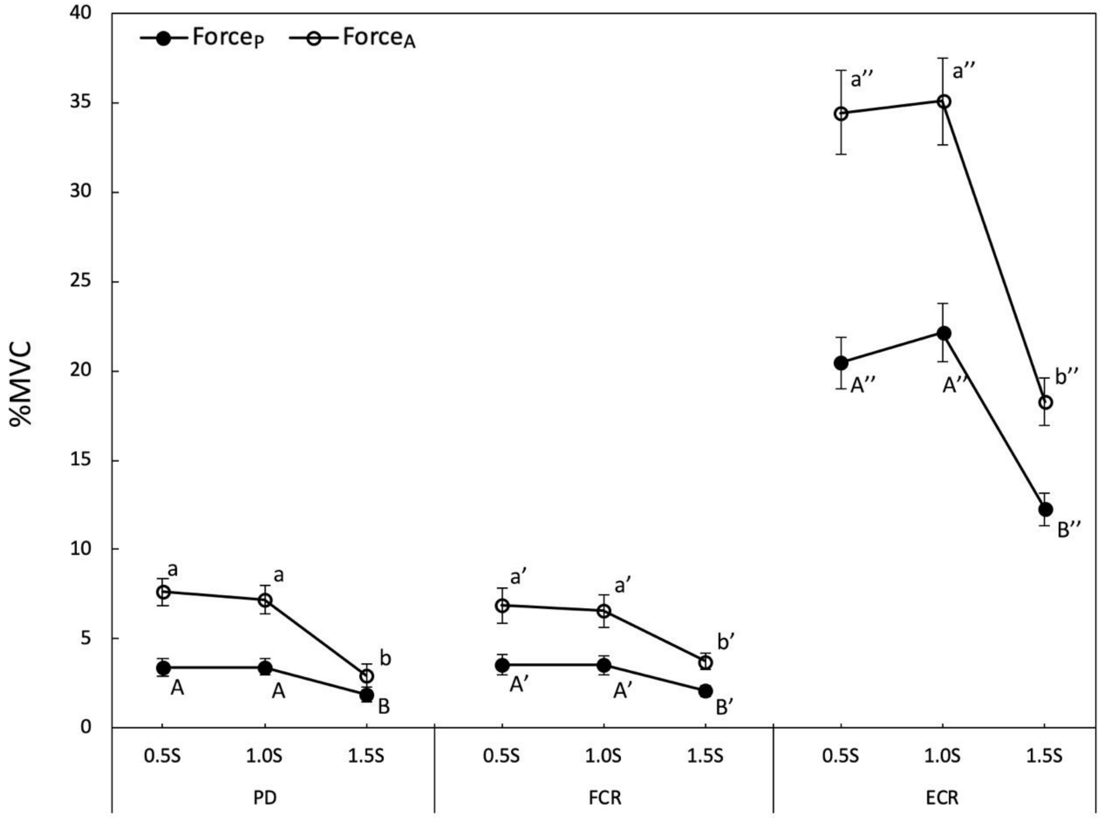


Figure 7.11 Effects of pulling duration on %MVC of PD, FCR, and ECR with Force$_P$ and Force$_A$ (SE range = 0.3-2.4)

For perceived comfort of shoulder with Force$_P$, pulling duration effect was significant (p=0.013; Table 7.1). Post-hoc analysis of the perceived comfort of shoulder with Force$_P$ showed that the pulling duration levels were statistically split into two groups (0.5 s-1 s and 1 s-1.5 s; Figure 7.12). The mean (SE) perceived comfort with 0.5 s was 4.9 (1.4), which was the highest, and that with 1.5 s was 4.8 (0.8), which was the lowest.

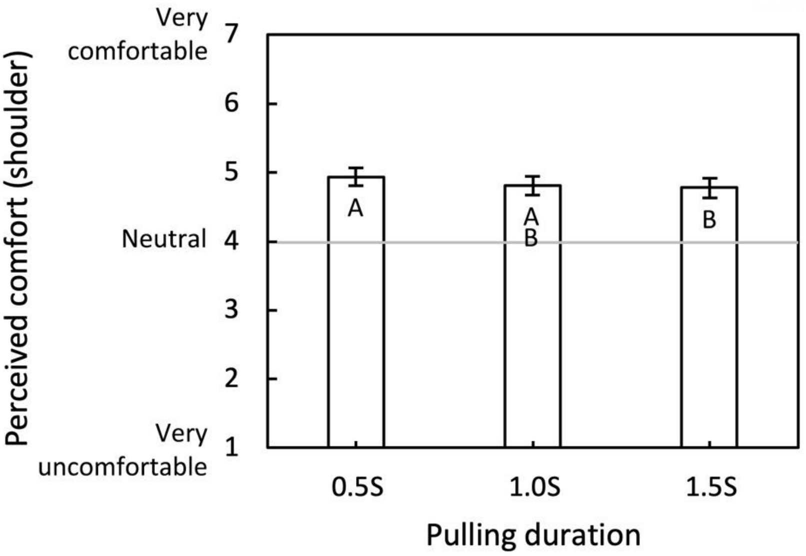


Figure 7.12 Effects of pulling duration on perceived comfort of shoulder with $Force_P$ (SE range = 0.8-1.6)

For perceived comfort of lower arm with $Force_P$, pulling duration effect was significant ($p=0.011$; Table 7.1). Post-hoc analysis of the perceived comfort of lower arm with $Force_P$ showed that the pulling duration levels were statistically split into two groups (0.5 s-1 s, and 1.5 s; Figure 7.13). The mean (SE) perceived comfort with 0.5 s was 4.4 (0.1), which was the highest, and that with 1.5 s was 4.2 (0.1), which was the lowest.

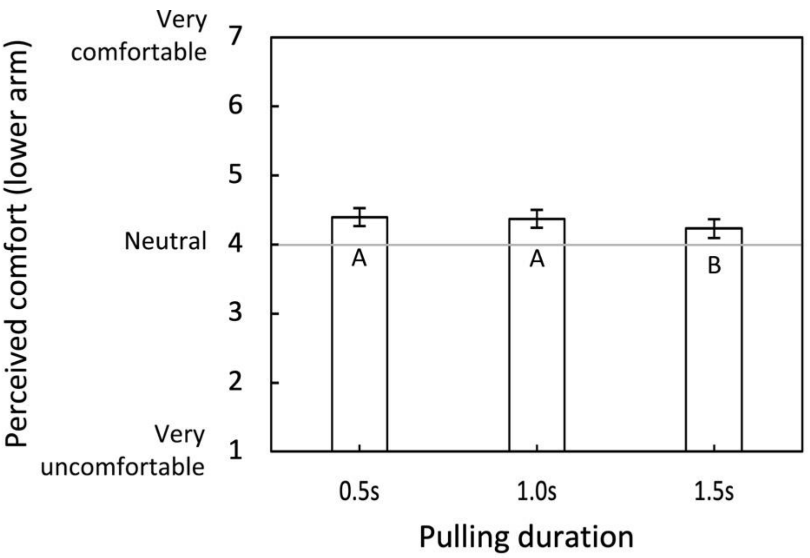


Figure 7.13 Effects of pulling duration on perceived comfort of lower arm when pulling with $Force_P$ (SE range = 0.13-0.14)

7.4. Discussion

This study examined the effects of gender, device thickness, and pulling duration on pulling forces, muscle activities, and perceived discomfort to determine user-preferred and acceptable screen pulling forces for rollable display devices to determine ergonomic rollable display device designs. In this section, the results of ANOVA and post-hoc tests are further explained and analyzed. Then, the design guidelines for rollable display devices in terms of pulling force are provided. Finally, the limitations of this study are addressed.

7.4.1. Overview of effects of gender, device thickness, and pulling duration

Among the three independent variables considered in this study (gender, device thickness, and pulling duration), pulling duration was most influential on the muscle activation, while gender was most influential on the perceived comfort for both $Force_P$ and $Force_A$.

Regarding $Force_P$, the effect of pulling duration and gender × device thickness was significant. Regarding %MVC of PD and FCR for $Force_P$, the effect of pulling duration was significant. Regarding %MVC of ECR for $Force_P$, the effect of gender, device thickness, pulling duration, and gender × pulling duration was significant. Based on the partial η^2 values (Table 7.1), pulling duration (partial η^2 = 0.584) largely accounted for %MVC of ECR for $Force_P$ relative to gender (partial η^2 = 0.262) or device thickness (partial η^2 = 0.318), indicating that pulling duration affects %MVC of ECR for $Force_P$ more than gender or device thickness do. Regarding perceived comfort of the shoulder, the effects of gender and pulling duration were significant. Based on the partial η^2 values (Table 7.1), gender (partial η^2 = 0.295) accounted well for perceived comfort of the shoulder for $Force_P$ relative to pulling duration (partial η^2 = 0.144), indicating that gender affects perceived comfort of the shoulder for $Force_P$ more than pulling duration does. Regarding perceived comfort of the upper arm, the effects of gender and device thickness were significant. Based on the partial η^2 values (Table 7.1), gender (partial η^2 = 0.434) largely accounted for perceived comfort of the upper arm for $Force_P$ relative to device thickness (partial η^2 = 0.124), indicating that gender affects the perceived comfort of the upper arm for $Force_P$ more than device thickness does. Regarding perceived comfort of the lower arm, the effects of gender and pulling duration were significant. Based on the partial η^2 values (Table 7.1), gender (partial η^2 = 0.173) accounted well for perceived comfort of the lower arm for $Force_P$ relative to pulling duration (partial η^2 = 0.148), indicating that gender affects the perceived comfort of the lower arm for $Force_P$ more than pulling duration does.

Regarding $Force_A$, there was no significant effect. Regarding %MVC of PD for $Force_A$, the effect of pulling duration was significant. Regarding %MVC of FCR for $Force_P$, the effects of device thickness and pulling duration were significant. Based on the partial η^2 values (Table 7.2), pulling duration (partial η^2 = 0.202) accounted well for %MVC of FCR for $Force_A$ relative to device thickness (partial η^2 = 0.135), indicating that pulling duration affects the %MVC of FCR for $Force_A$ more than device thickness does. Regarding %MVC of ECR for $Force_A$, the effects of gender, device thickness, pulling duration, and gender × pulling duration were significant. Based on the partial η^2 values (Table 7.2), pulling duration (partial η^2 = 0.488) largely accounted for %MVC of ECR for $Force_A$ relative to gender (partial η^2 = 0.349) or device thickness (partial η^2 = 0.155), indicating that pulling duration affects the %MVC of ECR for $Force_A$ more than gender or device thickness do. Regarding perceived comfort of the shoulder, upper arm, lower arm, wrist, and hand, the effect of hand was significant.

7.4.2. Gender × device thickness effect

Gender × device thickness effect was significant on $Force_P$ and perceived comfort of upper arm for $Force_P$ (p-value=0.049 and 0.048, respectively). For $Force_P$, although the gender × device thickness interaction effect was significant, device thickness seems to have a little influence in that 2-10 T were in the same group for each gender. Meanwhile, in the case of perceived comfort of upper arm, it did not show any significant difference among 2-10 T for Male, and perceived comfort of upper arm was significantly lower with 6-10 T than 2-6 T for Female. Using these results, rollable devices can be designed within the range of 2-10 T considering only perceived comfort for Male, but it can be seen that the range for Female should be thinner at 2-6 T.

7.4.3. Gender × pulling duration effect

Gender × pulling duration effect was significant on %MVC of ECR for both $Force_P$ and $Force_A$ (p-value = 0.011 and 0.005, respectively). For $Force_P$, %MVC of ECR was higher with 0.5 s-1.0 s than with 1.5 s for Female, but there was no difference for Male. This can be explained by the difference of muscle mass (see Section 7.4.4). For $Force_A$ however, %MVC of ECR showed significant difference among pulling duration not only for Female but also for Male (0.5 s-1.0 s and 1.0 s-1.5 s; Figure 7.4). Therefore, Male also shows a higher muscle activation at short pulling duration, similar to $Force_P$ for Female when they exert a relatively large force on themselves.

7.4.4. Gender effects

For both Force$_P$ and Force$_A$, the %MVCs of Female were significantly higher than those of Male. %MVC of PD, FCR, and ECR with Force$_P$ and Force$_A$ were compared (Figure 7.14). The ratio of %MVC (%MVC of Female/%MVC of Male) for PD, FCR, and ECR was 2.4, 1.4, and 2.0 for Force$_P$ and 1.7, 1.3, and 2.1 for Force$_A$, respectively.

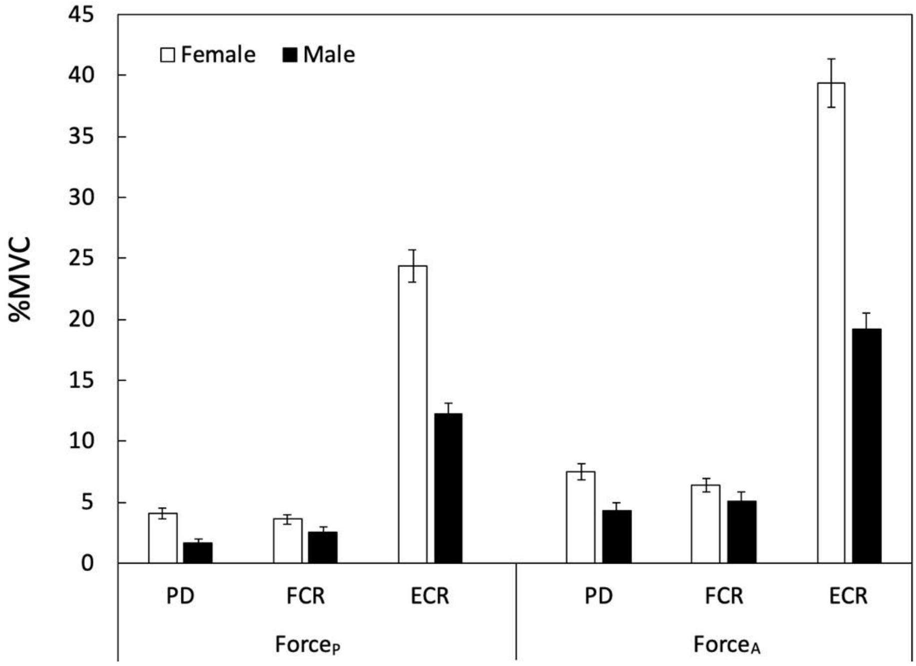


Figure 7.14 Comparison for %MVC of the three muscles PD, FCR, and ECR between Male and Female with Force$_P$ and Force$_A$.

As mentioned in the introduction, there is usually a difference in muscle mass between men and women. In a study by Gallagher et al. (1997), the appendicular skeletal muscle of 148 women (80 African-American and 68 Caucasian) and 136 men (72 African-American and 64 Caucasian) was measured, and mean (SD) arm muscle was 4.9 (1.1) kg for African-American women, 4.1 (1.0) kg for Caucasian women, 7.7 (1.4) kg for African-American men, and 7.2 (1.5) kg for Caucasian men. MVC also differed with the muscle mass between genders. In a study by Miller et al. (1993), elbow extension strength of women was found to be 52% of that of men, and women were found to be 70% and 80% as strong as men in the arms and legs, respectively. In a study by Heyward, Johannes-Ellis, and Romer (1986), women were found to be 54% as strong as men in the upper body and 68% as strong as men in the lower body. Sinaki et al. (2001) found that grip strength of men (women) ranged from 196-854 N (117-414 N) on the dominant side and 176-792 N (117-178 N) on the non-dominant side. The MVC difference between gender affect %MVC and perceived comfort as well. The formula of %MVC is given below.

$$\%MVC = \frac{Mean\ (RMS_{Task}) - Mean(RMS_{Ref})}{Mean\ (RMS_{MVC}) - Mean(RMS_{Ref})} \quad \text{(Sousa \& Tavares, 2012)}$$

If the force used in the task is the same, the numerator of the equation is the same, while the larger the muscle, the greater the value of RMS_{MVC}. Therefore, for Male, there was no significant difference of %MVC among three levels of pulling duration with $Force_P$ due to the large denominator compared to Female. However, it was expected that %MVC among three levels of pulling duration showed significant difference in that the nominator (RMS_{Task}) increased with $Force_A$. With both $Force_P$ and $Force_A$, perceived comfort of upper limb (from shoulder to hand) of Female was lower than that of Male (Male with a range of 4.7-5.5 and Female with a range of 3.6-4.2; see Figure 7.7). This can also be explained by the difference in muscle mass.

7.4.5. Device thickness effects

Regarding acceptable pulling, the effect of device thickness on %MVC of FCR was significant (p=0.017). Regarding both preferred and acceptable pulling, the effect of device thickness was significant on the %MVC of ECR (p=0.003 and 0.009, respectively). For perceived comfort of upper arm, device thickness effect was significant with $Force_P$ (p=0.025).

The higher the device thickness, the higher the %MVC of FCR with $Force_A$. %MVC of ECR was the lowest on 2-6 T compared to 6-10 T for both $Force_P$ and $Force_A$. Therefore, the range of 2 T is better than 6-10 T in terms of muscle activation. However, 2-6 T provided the highest perceived comfort of upper arm over 10 T. Comprehensively, 6 T is the recommended device thickness in consideration of muscle activation and perceived comfort.

7.4.6. Pulling duration effects

For $Force_P$, pulling duration effect was significant (p=0.022). For %MVC of PD, FCR, and ECR both with $Force_P$ and $Force_A$, pulling duration effects were significant (p<0.006). For perceived comfort of shoulder with $Force_P$, pulling duration effect was significant (p=0.013). For perceived comfort of lower arm with $Force_P$, pulling duration effect was significant (p=0.011).

When pulling duration was 1.0 s, $Force_P$ was the highest (1.5 s was in same group). During the pulling duration, different amounts of force were required between the pulling durations to unroll because the shorter the pulling duration, the faster the participant must unroll. However, unlike the expectation, $Force_P$ was the highest during 1.0 s. Thus, $Force_P$ differed as the pulling duration changed, and the specific range of pulling duration shows high $Force_P$, not just the shorter the pulling duration, the higher the $Force_P$. However, this result alone cannot determine whether high $Force_P$ is better than low $Force_P$. For high $Force_P$, it can be interpreted that users do not care if they give a high force, but it can be explained in reverse that they do require high force. Therefore, other factors such as %MVC or perceived comfort should be comprehensively considered to define the range of $Force_P$ for better UI.

From the perspective of muscle activation, 1.5 s provided the lowest %MVC for both $Force_P$ and $Force_A$. Therefore, the longer the pulling duration, the lower the users' willingness to empower. However, this does not represent the total amount of muscle activation because the pulling duration was different. This result cannot explain whether users prefer the unrolling motion with short pulling duration-high muscle activation or long pulling duration-low muscle activation. Therefore, perceived comfort was considered simultaneously.

From the perspective of perceived comfort, 1.5 s also provided the lowest perceived comfort of shoulder and lower arm with $Force_P$. Therefore, it can be found that users prefer short pulling duration with high muscle activation over long pulling duration with low muscle activation when unrolling. The range of %MVC ratio between $Force_P$ and $Force_A$ of 3-level pulling duration of PD, FCR, and ECR (%MVC with $Force_A$ / %MVC with $Force_P$) was 1.6-2.2, 1.8-1.9, and 1.5-1.7, respectively. In the case of PD and FCR, the maximum %MVC was 7.6 (%MVC of PD in 0.5 s with $Force_A$), but this was still very low compared with MVC. In the case of %MVC of ECR however, the maximum %MVC was 35.1 (in 1.0 s with $Force_A$), but perceived comfort of shoulder and lower arm still describe the shorter pulling duration as better. Therefore, in the unrolling motion, most users prefer short pulling duration with less considering muscle usage.

7.4.7. Pulling forces

The 5th percentile, 95th percentile, mean (SE) $Force_P$ and $Force_A$ were calculated (Figure 7.15).

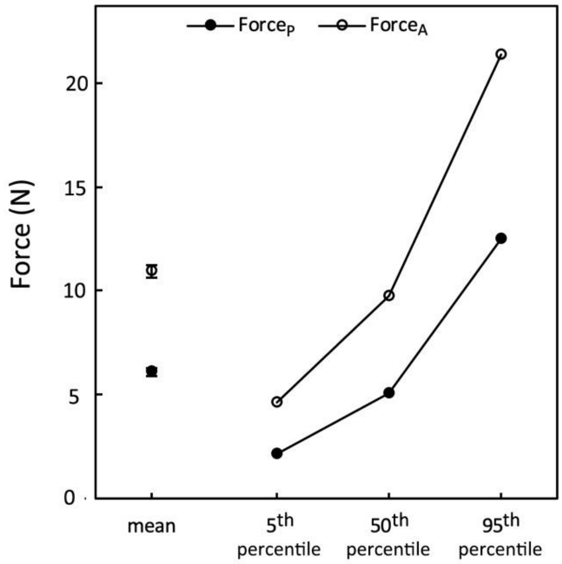


Figure 7.15 Mean and percentile values for Force$_P$ and Force$_A$ (SE ranges = 0.2–0.32).

The mean (SE) Force$_P$ was 6.1 N (0.2), and the range of 5th-95th percentile of Force$_P$ was 2.1-12.5 N. The mean (SE) Force$_A$ was 10.9 N (0.2), and the range of 5th-95th percentile of Force$_A$ was 4.6-21.4 N. The ratio of Force$_A$/Force$_P$ was 1.8, indicating that users can afford to empower 1.8 times the preferred pulling force when unrolling.

7.4.8. Limitations

This study had some limitations. First, the weights of the three prototype devices were light and different to each other, with the weights of 2 T, 6 T, and 10 T being 9, 16, and 28 g, respectively. The mean (SD) weight of 286 smartphone models released by the top five smartphone manufacturers worldwide is 140.5 (37.0) g (Studies 4-5). Hence, an additional study using prototypes with heavier weights is also required. Secondly, only younger individuals were considered. Preferred and acceptable pulling force of older individuals might be different from that of younger individuals considering the aging factors (e.g., decreased muscle size). Thirdly, only Koreans were considered. Each ethnic group has distinct hand anthropometric dimensions in terms of size, proportion, shape, and obesity (Davies, Abada, Benson, Courtney, & Minto, 1980; Courtney, 1984). Fourthly, the posture may not reflect the exact same posture of real usage. In order to reduce other potential factors (e.g., placing arm on the table or thigh), the position was fixed as explained in the experimental procedure (7.2.4). However, posture must be more freely chosen when using the real smart device. Therefore, various situations should be considered. Despite these limitations, the fundamental findings of this study will be useful for designing ergonomic rollable display devices.

7.5. Conclusion

This study considered the effects of gender, device thickness, and pulling duration on pulling forces, muscle activities, and perceived discomfort to determine user-preferred and acceptable screen pulling forces for rollable display devices and ergonomic rollable display device design requirements. Pulling duration largely accounted for %MVC of PD, FCR, and ECR while gender largely accounted for perceived comfort. In consideration of perceived comfort, the device thickness was recommended as 2-6 T for all genders. %MVC of PD, FCR, and ECR of Female were 1.4-2.4 times higher than those of Male. Perceived comfort of Female (3.6-4.2) was 1.1-1.3 times higher than that of Male, but the range of that was near neutral (4). Although %MVC was higher at a pulling duration of 0.5 s than at 1.0-1.5 s, perceived comfort was also higher at 0.5 s, indicating that short pulling duration-high muscle activation is better than long pulling duration-low muscle activation for the unrolling motion in the force range of $Force_P$ and $Force_A$. Comprehensively, 6 T was the best thickness in consideration of muscle activation and perceived comfort. These findings will facilitate the design and UI of ergonomic rollable display devices in terms of pulling force.

Chapter 8. General Discussion and Conclusions

8.1. General discussion

The major goal of this study was to develop ergonomic design guidelines for current non-flexible smartphone and future smart devices with flexible displays, by evaluating a variety of factors related with UI/UX.

Six studies were conducted in a laboratory environment. Studies 1 and 2 were about current non-flexible smartphones. Study 1 (Chapter 2) examined the effects of task type (neutral, comfortable, maximum, vertical, and horizontal strokes), phone width (60 and 90 mm), and hand length (small, medium, and large) on grasp, index finger reach zone, discomfort, and muscle activation during such interaction. Study 2 (Chapter 3) examined the ergonomic smartphone forms by investigating the effects of hand length, four major smartphone dimensions (height, width, thickness, and edge roundness), and smartphone mass on grip comfort and design attractiveness. Studies 3-6 were about future mobile devices with flexible displays (foldable and rollable). Study 3 (Chapter 4) was conducted to determine ergonomic forms for mobile foldable display devices in terms of comfort and preference. Study 4 (Chapter 5) examined the effects of gripping condition, device thickness, and hand length on bimanual grip comfort when using mobile devices with a rollable display. Study 5 (Chapter 6) examined the effects of device height (70, 140, and 210 mm), task (web searching, video watching, and E-mail composing), and hand length (small, medium, and large hand groups) on various UX elements associated with using rollable display devices. Study 6 (Chapter 7) examined the effects of gender (15 males and 15 females), device thickness (2 T, 6 T, and 10 T), and pulling duration (0.5 s, 1.0 s, and 1.5 s) on preferred and acceptable pulling forces, muscle activities, and perceived discomfort of the upper limbs associated with unrolling rollable displays.

In this general discussion, the three types of independent variables, object, task, and hand, are further considered.

8.1.1. Shapes and dimensions of smart device (object)

Over time, the dimensions of smartphones have changed. Starting with the iPhone (Apple, Inc., USA), known as the first smartphone, a number of smartphone models have been released around the world. Among the smartphones released from 2007 to 2018, the screen sizes of 804 smartphones launched by the top 5 manufacturers are summarized in Figure 8.1. Among the tablet PCs released from 2010 to 2018, the screen sizes of 170 tablet PCs released by the top 5 manufacturers are also summarized in Figure 8.1.

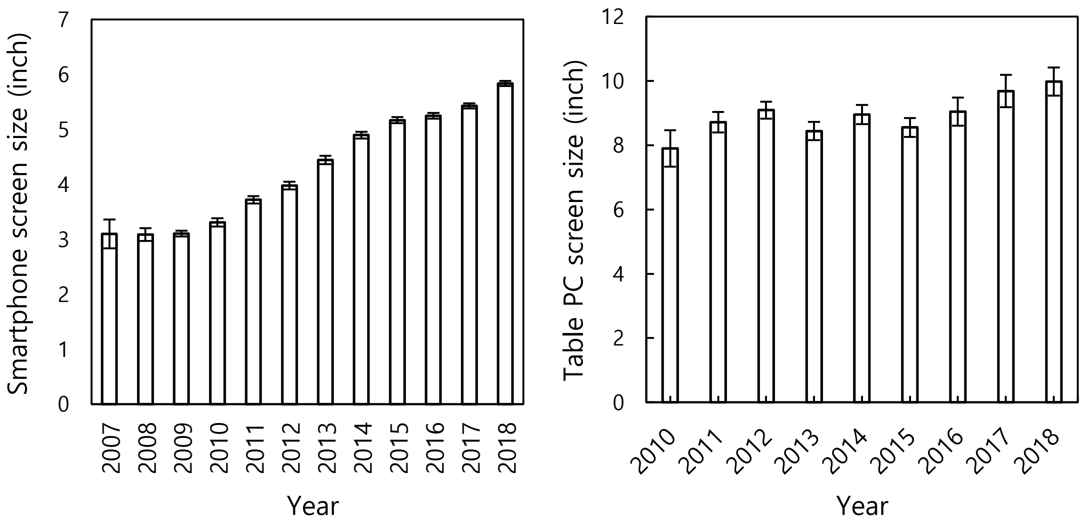


Figure 8.1 Change of screen size of smartphones and Tablet PCs by year

As mentioned in the previous chapters, and as seen in Figure 8.1, the screens of smartphones are growing. If the screen is larger than a certain size, the grip comfort and portability become very poor. As shown in the results of Studies 2 and 6 however, a certain standard smartphone is suitable for usability. Through Study 2, it was found that the specific size of the smartphone provides high grip comfort (140 H × 65 (or 70) W × 8 T × 2.5 R). In Study 6, users preferred a specific size of smart device with rollable display (140 H×142 W; 140 H×206.2 W recommended in consideration of 95th percentile of preferred screen width). It is expected that next-generation displays such as the foldable or rollable display can compromise the contradiction among the needs of large screen size and those of portability and grip comfort.

In Study 1, subjective discomfort increased with the 90-mm-wide device, and the FDI was highly activated with the 60-mm-wide device. Finally, the specific range of input (best location for rear interaction) was suggested. In Study 2, the size of the smartphone affected the grip comfort. The dimensions optimizing grip comfort and design attractiveness were 140 H × 65 (or 70) W × 8 T × 2.5 R. In Study 3, the structure of mock-up (folding methods) affected the preference, and the best folding method was Z-type. In Study 4, device thickness affected grip comfort (for the right hand with $Grip_{FF}$, the thicker the device, the higher the grip comfort). In Study 5, device height affected preferred screen width (mean (95th percentile) preferred screen width of three device heights were 70 H×70.7 (100.0) W, 140 H×142.0 (206.2) W, and 210 H×207.2 (311.1) W). Comprehensively, 140 H×206.2 W was recommended. In Study 6, device thickness affected the muscle activation and perceived comfort, and a device thickness of 6 T was the best. Smart devices were the main topic of all six studies, but the details of device shapes were different. Nonetheless, the dimensions or shapes of the devices affected muscle activation and perceived discomfort in all studies, and the specific value or range of preferred dimensions or shapes were defined in all cases. Therefore, it is necessary to carry out the experiments considering the dimensions or shapes of the product, not only for the improvement of existing products but also for the development of next-generation products.

8.1.2. Smartphone as a multi-tasking device (task)

The smartphone is a versatile device that performs a variety of tasks in addition to phone functions. It has evolved into a hand-held multi-functional device that contains computers and other devices, such as cameras, e-books, and document work, which are unrelated to the main phone function of calling. The tablet PC is a device that can work effectively with a larger display than the smartphone, which is a portability-based display device. Therefore, smart devices should be improved in a suitable form in consideration of various tasks.

This study covered various tasks from simple grip or touch to practical tasks such as E-mail sending or web searching. In Study 1, task was composed of five basic motions that make up practical application usage (neutral stroke, comfortable stroke, maximum stroke, horizontal stroke, and vertical stroke). The range of index finger reach zones (touch area) varied by the task. In reality, horizontal and vertical stroke were not parallel to the device's X- and Y-axes. As mentioned earlier, different tasks used different muscles. In Studies 2 and 3, task was not an independent variable. In Study 4, grip regions and grip comfort were significantly different depending on the gripping methods. In Study 5, three practical tasks (web searching, video watching, and E-mail sending) were used. $\text{Task}_{\text{Video}}$ was recommended to use the screen aspect ratio of 1.4, which was wider than that of $\text{Task}_{\text{Search}}$ and $\text{Task}_{\text{Mail}}$ (screen aspect ratio of 1.2), indicating that it will be the good function to change the screen aspect ratio for each application in the rollable device. In Study 6, the tasks were the same in terms of pulling motion, but the pulling duration was considered at three levels, short (0.5 s) to long (1.5 s). The longer the pulling duration, the lower the muscle activation. However, the longer the pulling duration, the lower the perceived comfort. Therefore, in the unrolling motion, users preferred short pulling duration with less considering muscle usage.

8.1.3. Should hand anthropometry be considered for ergonomic experiments? (hand)

The hand is the body part that directly touches the mobile device. In this study, one-handed grip postures used for a static task (calling; Study 2), grip postures used for simple input tasks (Studies 1 and 3), and bimanual grip postures involving shoulder external rotations (Studies 4-6) were considered.

In Study 1 (about rear interaction of non-flexible smartphone), the size of the touch area by the index finger during each task varied by hand length levels. During the comfortable stroke, the reach envelope was the widest for the small hand group. In contrast, during the maximum stroke, the reach envelope was the widest for the large hand group, mostly due to longer index fingers at higher hand length levels. In addition, after using a 90 mm-width (wide) smartphonephone, the small hand group reported higher discomfort ratings than the other two groups did (50.24 vs. 38.85) and also reported discomfort ratings in the range of 10.2 (neutral stroke) to 62.8 (maximum stroke) for the 60mm-width (narrow) smartphonephone in the range of 22.1(neutral stroke) to 81.0 (maximum stroke) for the 90mm-width phone. In Study 5, hand length significantly affected the preferred screen width. The larger the hand length, the wider the preferred screen width. In Study 6, gender significantly affected the perceived comfort. %MVC of PD, FCR, and ECR of the female group was 1.4-2.4 times higher than that of the male group. Perceived comfort of the female group (3.6-4.2) was 1.1-1.3 times higher than the male group. In Studies 2, 3, and 4 however, hand length did not show any significant difference. As a result, hand length effect could exist depending on the specific topic (purpose) of each study and the experimental environment (such as subject ethnicity and age). Hand is the body part directly in touch with the device. Therefore, usability studies should consider the effect of hand length as one of the main factors.

8.2. Conclusions

8.2.1. Major outcomes

The ultimate goal of this study was to determine the ergonomics of smartphones and next-generation smart devices regarding UI/UX to develop ergonomic design guidelines. The major findings are given below.

An ergonomic smart device design could improve user interface and user experience. Study 1 was on the rear interaction of non-flexible smartphones. The location of rear interaction of non-flexible smartphones was defined as 8.8–10.1 cm from the bottom and 0.3–2.0 cm to the right of the vertical center line (0.3–2.0 cm to the left for left-handed individuals). Since the horizontal and vertical strokes with rear interaction were not parallel to devices' X- and Y-axes, the input recognition should be defined to consider the sloped angle. During T_H, slopes were made in the range from −10.8° to −13.5° with reference to the X-axis, and during T_V, slope was made in the range from −1.6° to −8.4° with reference to the Y-axis. Study 2 considered the best size for non-flexible smartphones. The dimensions optimizing grip comfort and design attractiveness were 140 H × 65 (or 70) W × 8 T × 2.5 R. The most preferred mass was 122 g (in the range 106–137 g). The horizontal perimeter of 146 mm was associated with high grip comfort and design attractiveness. This value lies in the middle of the cylindrical handle circumference range that has previously demonstrated high grip force and comfort (140–151 mm). Study 3 was for defining the most preferred folding method for foldable display devices. Preferred screen size during calling was 140 H × 65 W, and for web searching and gaming it was 140 H × 130 W. The Z-type folding method was recommended, which provided small-to-large screen sizes (5.3" – 9.0" or 13.5 cm – 22.9 cm) as well as high folding/unfolding preference. Study 4 was for defining the grip region of the rollable display device. Side bezel width (horizontal grip width) was recommended to be a minimum of 20 mm, and the vertical grip part was recommended to have 123.6 mm $Grip_{FF}$. Side bezel width and vertical grip part were recommended as 14 and 113.6 mm, respectively for $Grip_{MM}$. Side bezel width and vertical grip part of the right hand were recommended as 14.6 and 95.6 mm, respectively for $Grip_{FP}$. Considering grip comfort, the recommendation for $Grip_{FF}$ was the best grip region. Device thickness of 10 mm is recommended. Study 5 was for defining the preferred screen width for rollable display devices and tasks. The preferred screen width of three device height (70 mm, 140 mm, and 210 mm) was 70.7 mm, 142.0 mm, and 207.2 mm, respectively. To cover the 95th percentile of the results, 100.0mm, 206.2mm, and 311.1mm were recommended as the maximum screen widths. The recommended (maximum) preferred screen aspect ratio of three device heights (70 mm, 140 mm, and 210 mm) was 1.4 (2.0), 1.2 (1.7), and 1.1(1.6), respectively. For $Task_{Video}$, the screen aspect ratio of 1.4 was recommended, which was wider than for $Task_{Search}$ and $Task_{Mail}$ (screen aspect ratio of 1.2). The mean (SE) preferred screen width for $Hand_S$, $Hand_M$, and $Hand_L$ was 127.9 (6.6), 135.9 (7.4), and 156.0 (8.4), respectively. A device (screen) height of 140 (120) mm with a width of 142 mm screen improved the overall user experience. Study 6 was for defining the preferred and acceptable pulling force for rollable display devices. Short pulling duration (0.5 s in this study) was recommended. Comprehensively, 6 T was the best thickness in consideration of muscle activation and perceived comfort. The preferred pulling force was 6.1 N, and the range of the 5th-95th percentile was 2.1-12.5 N. The acceptable pulling force was 1.8 times higher than the preferred pulling force, which can be used as the threshold of pulling force.

Based on the above findings, specific guidelines were suggested for each study.

Guidelines for rear interactions of non-flexible smartphones

- The location of rear interaction of non-flexible smartphone should be 8.8–10.1 cm from the bottom and 0.3–2.0 cm to the right of the vertical center line (0.3–2.0 cm to the left for left-handed individuals).

- The range of the angle for recognizing the horizontal and vertical strokes should be defined by the range −10.8° to −13.5° with reference to the X-axis for horizontal strokes and the range −1.6° to −8.4° with reference to the Y-axis for vertical strokes.

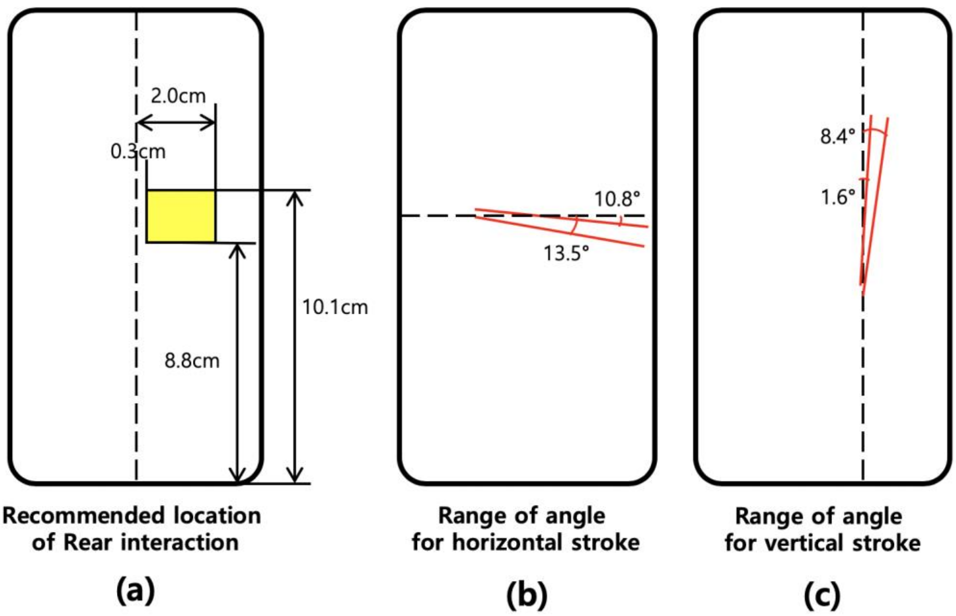


Figure 8.2 (a) Recommended location of rear interaction, (b) range of angles for horizontal strokes, and (c) range of angles for vertical strokes

Guidelines for smartphone dimensions

- The dimensions of smart devices should be 140 mm (H) × 65 mm (or 70 mm) (W) × 8 mm (T) × 2.5 mm (R) to optimize one-handed grip comfort and design attractiveness.

- The mass of smart devices should be 122 g (in the range 106–137 g).

- The horizontal perimeter should be 146 mm, which provides high grip comfort and design attractiveness.

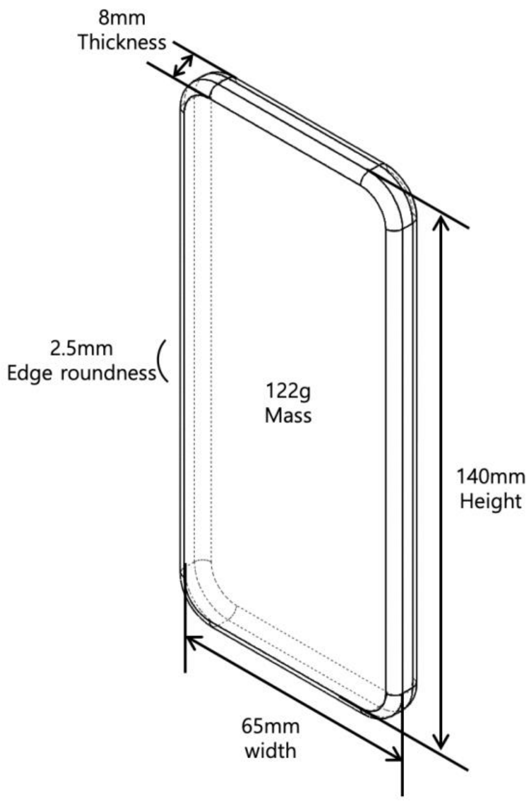


Figure 8.3 The recommended smartphone dimensions and mass considering one-handed grip comfort

Guidelines for foldable display devices

- Device size (screen size) for foldable display devices should be 140 H × 65 W (120 H×60 W) for calling and 140 H × 130 W (120 W×128 W) for web searching and gaming.

- The folding method should be Z-type, which provides small-to-large screen sizes (5.3" – 9.0" or 13.5 cm – 22.9 cm) as well as high folding/unfolding preference.

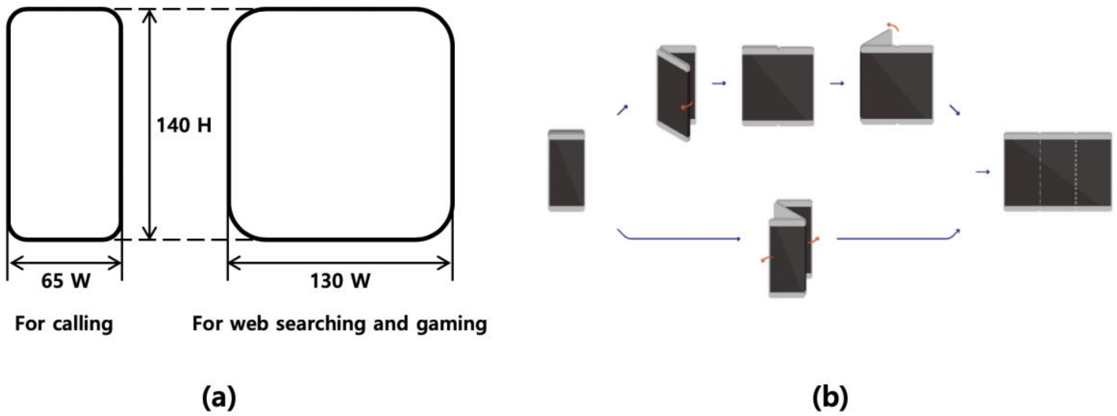


Figure 8.4 (a) The recommended device size and (b) folding method (Z-type)

Guidelines for rollable display device: Gripped region

- The size bezel width should be a minimum of 20 mm for horizontal grip width and 123.6 mm for vertical grip width with Grip$_{FF}$ (gripping both sides of the device freely; unrestricted gripping).

- The size bezel width should be a minimum of 14 mm for horizontal grip width and 113.6 mm for vertical grip width with Grip$_{MM}$ (gripping both sides of the device minimally; restricted gripping).

- The size bezel width should be a minimum of 14.6 mm for horizontal grip width and 95.6 mm for vertical grip width with Grip$_{FP}$ (gripping the left side freely and pinch-gripping the right side; pinch gripping).

- Device thickness should be 6-10 mm.

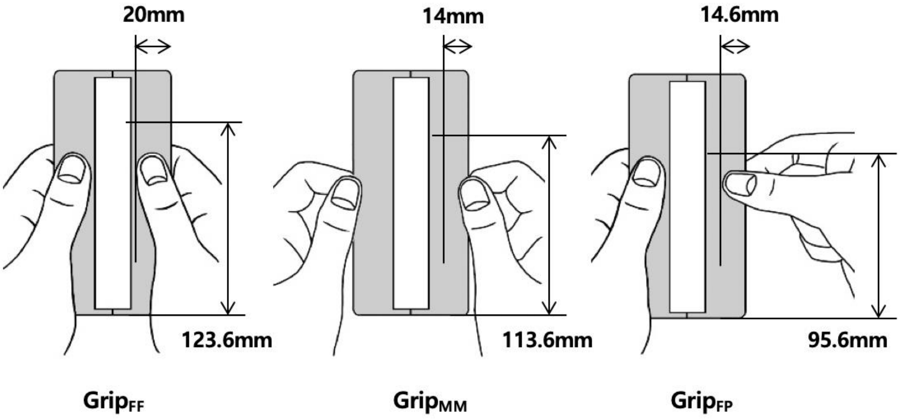


Figure 8.5 Recommended width and height of side bezel for three gripping conditions

Guidelines for rollable display device: Preferred screen size

- To cover the 95th percentile of preferred screen width, the screen width of three device heights should be 100.0 mm, 206.2 mm, and 311.1 mm as the maximum screen width. Mean screen width of three device heights (70 mm, 140 mm, and 210 mm) was 70.7 mm, 142.0 mm, and 207.2 mm, respectively.

- To cover the 95th percentile of preferred screen aspect ratio, screen aspect ratio of three device heights should be 2.0, 1.7, 1,6 as the maximum screen aspect ratio. The mean screen aspect ratio of three device heights (70 mm, 140 mm, and 210 mm) was 1.4, 1.2, and 1.1, respectively.

- To cover the 95th percentile of preferred screen aspect ratio, screen aspect ratio of $Task_{Video}$, $Task_{Search}$, and $Task_{Mail}$ should be 1.8, 1.9, and 2.0, respectively. Mean screen aspect ratio of $Task_{Video}$, $Task_{Search}$, and $Task_{Mail}$ was 1.4.

- Screen width for $Hand_S$, $Hand_M$, and $Hand_L$ should be 250.7, 256.7, and 282.5, respectively (mean screen width for $Hand_S$, $Hand_M$, and $Hand_L$ was 127.9, 135.9, and 156.0, respectively).

- Device size should be 140 H × 206.2 W, which improved the overall user experience, and accommodate different tasks and diverse user needs.

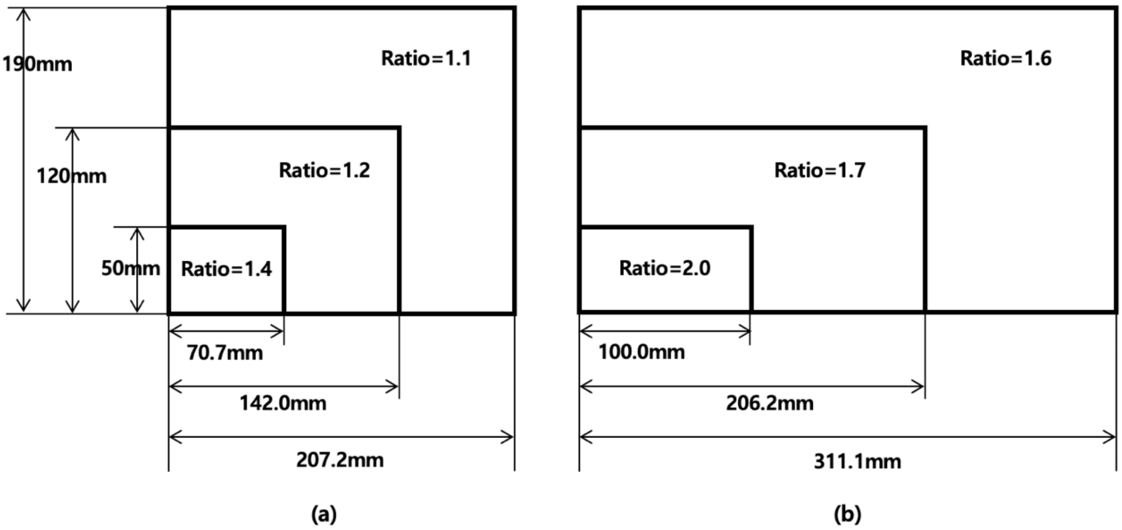


Figure 8.6 (a) Mean screen width for three device height levels and (b) recommended screen width for three device height levels to accommodate the 95th percentile preferred screen width.

Guidelines for rollable display device: Pulling force

- Pulling duration should be short (0.5 s rather than 1.0-1.5 s, as considered in this study).

- Device thickness should be 6 T in consideration of muscle activation and perceived comfort.

- Pulling force should be 6.1 N (preferred pulling force) or 12.5 N (to cover 95th percentile pulling force). In consideration of acceptable pulling force, pulling force should be 1.8 times as high as preferred pulling force.

8.2.2. Limitations

This study had some limitations. The limitations of Studies 1-6 can be categorized by object, task, and hand.

Object

First, in all six studies, low-fidelity prototypes were used. Especially in Studies 3-6, a practical usage scenario could not be used because foldable and rollable displays have not yet been released as products. However, formative usability evaluations using low-fidelity prototypes (e.g., paper prototypes) are effective in user experience studies when actual products are absent (Snyder, 2003). Secondly, smartphone weight was not considered for Studies 1, 3, 4, 5, and 6. The weight could not be manipulated or controlled because the prototypes were made of ABS plastic. The size-weight illusion (where larger objects of equal weight feel lighter than smaller ones; Charpentier, 1891) should be considered as well as device weight, especially because the size of foldable and rollable display devices is changeable. Furthermore, the mean (SD) weight of 286 smartphone models released by the top five smartphone manufacturers worldwide is 140.5 (37.0) g, and the weight range is 75–500 g. Hence, an additional study using heavier prototypes (≥75 g) is also required. Thirdly, although there may be diverse factors affecting the grip comfort and design attractiveness of smart devices, only the basic major phone dimensions (e.g., phone height, width, thickness, and edge roundness) were manipulated or controlled. For example, the shape and location of screen curvature could also affect grip comfort (Yi et al., 2017). Furthermore, there are various other factors such as color, novelty, brand, and other form factors (e.g., display ratio, button shapes and sizes, and materials; Chuang, Chang, & Hsu, 2001; Shinder, 2010; Hassan, 2015). Fourthly, in Studies 4 and 5, the force of the spring for screen retraction was approximately 2.5 N, and the gripping method and grip comfort could change according to the required pulling force (Kong, Kim, Lee, & Jung, 2012; Dianat, Nedaei, & Nezami, 2015).

Task

First, all six studies considered the ‘sitting without desk’ condition but did not consider other states (such as walking). Secondly, as mentioned above, practical tasks could not be adapted to experiment due to the low-fidelity prototypes. Thirdly, longer-term grip or task duration should also be considered: previous studies on grip comfort have used durations ranging from 3 seconds to 10 minutes, and viewing duration used in the display evaluation was very wide, ranging from 10 seconds to 4 hours (Ardito et al., 1996; Bracken, 2005; Kwon and Lee, 2007; Cho et al., 2010; Fröhlich et al., 2012; Lambooij, Ijsselsteijn, and Heynderickx, 2011; Tam et al., 2011; Lambooij, Ijsselsteijn, and Heynderickx, 2011; Sakamoto et al., 2012; Yand and Chung, 2012; Hou et al., 2012; Zhang, Christou, 2014; Liu, et al., 2015; Oh and Lee, 2016). Since video watching often lasts for a long time, further research on long-term watching is required. Although the 10-second grip duration used in this study is not too short, additional research is required to investigate longer-term grips. Fourthly, the screen/device orientation was not considered. Only bimanual screen unrolling on a transverse plane (using the device in landscape mode), but not on a sagittal plane (using the device in portrait mode) was investigated in this study. Therefore, it is necessary to examine the effects of the screen unrolling direction on the grip regions and grip comfort

Hand

First, in all six studies, only Korean individuals in their 20s participated. Other factors such as ethnic group and age group could derive different results. Secondly, all participants were right-handed. Though approximately 90% of the population is right-handed (Holder, 2001; Hardyck & Petrinovich, 1977), left-handedness should be considered for universal designs. Thirdlu, in Studies 1-5, the ratios of men to women in three hand groups were not well balanced.

8.2.3. Expected contributions and future work

This work will contribute to determining tangible UX/UI designs for current non-flexible smartphones as well as future flexible display devices considering perceived grip comfort, user preference, attractive design, and/or muscle activities. The findings of Study 1 can be used to determine the proper location for rear interaction regarding muscle activation and subjective discomfort. The findings of Study 2 can be used to determine the proper smartphone size regarding one-handed grip comfort. The findings of Study 3 can be used to determine the most user-preferred structure for foldable display devices. The findings of Study 4 can be used to determine the size of the grip region for rollable display devices regarding grip comfort. The findings of Study 5 can be used to determine the overall device height and screen width of rollable display devices regarding preference, grip comfort, user satisfaction, portability, and design attractiveness. The findings of Study 6 can be used to determine the pulling force for unrolling the devices. The developed guidelines in this thesis will be beneficial for human factor engineers and UI/UX designers, allowing them to design non-flexible smartphones and next-generation display devices.

Future works are warranted to address the limitations of this thesis and to complete mobile UX designs. First, various ethnic groups should be considered (for universal design or design for all). As smartphones (smart devices in the future) have become an indispensable product to humans, satisfactory usability should be provided to as many people as possible. Secondly, various dimensions or factors of smart devices should be considered. The effects of other potential factors (e.g., texture of device surface and double curvature) should be investigated. Thirdly, high-fidelity prototypes should be used to increase validity. Fourthly, more practical tasks based on well-made scenarios should be used. Lastly, it is necessary to study the intangible UX for future mobile devices by investigating the GUI based on the PUI proposed in this study.

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