Applied Ergonomics 67 (2018) 142–150

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Smartphone form factors: Effects of width and bottom bezel on touch performance, workload, and physical demand

Seul Chan Lee[a], Min Chul Cha[a], Hwan Hwangbo[a], Sookhee Mo[b,*], Yong Gu Ji[a]

[a] Department of Industrial Engineering, Yonsei University, Seoul, South Korea
[b] Graduate Program in Technology Policy, Yonsei University, Seoul, South Korea

ARTICLE INFO

Keywords:
Smartphone form factor
Touch behavior performances
One-handed interaction

ABSTRACT

This study aimed at investigating the effect of two smartphone form factors (width and bottom bezel) on touch behaviors with one-handed interaction. User experiments on tapping tasks were conducted for four widths (67, 70, 72, and 74 mm) and five bottom bezel levels (2.5, 5, 7.5, 10, and 12.5 mm). Task performance, electromyography, and subjective workload data were collected to examine the touch behavior. The success rate and task completion time were collected as task performance measures. The NASA-TLX method was used to observe the subjective workload. The electromyogram signals of two thumb muscles, namely the first dorsal interosseous and abductor pollicis brevis, were observed. The task performances deteriorated with increasing width level. The subjective workload and electromyography data showed similar patterns with the task performances. The task performances of the bottom bezel devices were analyzed by using three different evaluation criteria. The results from these criteria indicated that tasks became increasingly difficult as the bottom bezel level decreased. The results of this study provide insights into the optimal range of smartphone form factors for one-handed interaction, which could contribute to the design of new smartphones.

1. Introduction

The data usage of smartphones has recently exceeded that of desktop computers as the number of smartphone users has increased. In other words, smartphones have become the primary device for information consumption and sharing. In addition, many people prefer to use smartphones for contents and activities such as games, media, blogging, or social networking services. Consequently, smartphone displays have increased in size because users prefer larger displays for consuming a variety of contents. In fact, the average screen size of a smartphone was 2.59 in. in 2007 and increased to 4.86 in. by 2014 (Victor, 2014).

Although a large display is convenient for accessing a variety of contents, from an ergonomic point of view, the increase in display size may cause users several difficulties in device utilization. Considering that a one-handed grip is widely used for smartphones (Steven, 2013), increasing the device size could negatively affect the grip comfort and increase the physical demand required in using a smartphone (Kietrys et al., 2015; Kwon et al., 2016; Pereira et al., 2013). Previous studies evaluated the physical demand considering one-handed interactions with a smartphone device. Kietrys et al. (2015) studied the effects of the input device type (physical keypad and touch screen), texting style, and screen size on muscle activities, confirming that there was an increase in muscle activities according to increasing screen size. Kwon et al. (2016) tested the effects of the curvature rate of a smartphone on hand comfort by assuming that the curvature rate will decrease hand fatigue when smartphone has a large-screen. When the curvature was moderate, less muscle activity was recorded compared with a flat device. Pereira et al. (2013) concluded that increasing the tablet size decreased usability and worsened biomechanics in terms of increased fatigue in the neck and shoulder regions.

Smartphone users have experienced inconveniences related to not only the physical aspects but also the usability of the device (Chiang et al., 2013; Oehl et al., 2007; Pereira et al., 2013; Xiong and Muraki, 2016). Chiang et al. (2013) conducted a touch pointing experiment with one-handed interaction by using 10 smartphone devices with size ranging from 2.5 to 5.3 in. Their results showed that the error rate and task completion time increased according to increasing screen size. Xiong and Muraki (2016) analyzed the thumb movement coverage on smartphone touch screens with a one-handed grip. They found that, although the thumb-coverage area has increased, the coverage area did not increase as much as the screen size has increased. Therefore, difficulty in tapping icons located on the edge of the screen can be expected.

* Corresponding author. Graduate Program in Technology Policy, Yonsei University, 262 Seongsanno, Seodaemun-gu, Seoul 120-749, South Korea.
E-mail address: soohmo6@gmail.com (S. Mo).

http://dx.doi.org/10.1016/j.apergo.2017.10.002
Received 3 April 2017; Received in revised form 24 July 2017; Accepted 3 October 2017

In addition, many studies have demonstrated that Fitts' law applies to pointing interactions in mobile devices and touch screens (Lin et al., 2007; Oehl et al., 2007; Perry and Hourcade, 2008; Trudeau et al., 2016). According to Fitts' law, the task difficulty increases as the target distance increases. Therefore, large-sized screens include increased marginal areas for icons, resulting in increasing task difficulties.

Increasing display size will likely lead to the increase in device size, and it is unclear whether the negative impact on user performance is a result of the display size or the device size. However, previous studies focused on the effects of display size without considering device size variables (Kietrys et al., 2015; Xiong and Muraki, 2016). Therefore, the relationship between device size and user performance needs to be investigated.

Because the size of the display cannot be continuously increased, smartphone companies have tried to increase the screen-to-body size ratio in order to minimize the effects of increasing the screen size on increasing device size. Initial models of smartphones had about a 60% screen-to-body size ratio; however, most smartphones today exceed 70% (Petrovan, 2015). In particular, there is a new trend in designing displays that aim to increase the ratio, such as using edge displays or increasing the smartphone length. However, the physical bezel area decreases as the screen-to-body size ratio increases. Physical bezels play a role not only in protecting the screen area but also in improving usability. Users hold smartphones by the physical bezel. If the physical bezel area decreases, then interaction with the device becomes more difficult because the user's palm will touch the screen (Nick, 2012).

Whether these changes in smartphone form factors (FF)—increased display size and reduced physical bezel—would be ergonomically appropriate is unclear. However, there are few studies on the effects of these FF. Therefore, this study investigated the appropriateness of FF, and aimed to provide guidelines for mobile devices from an ergonomic perspective. Specifically, the width level was selected as a device size factor and the bottom bezel as a physical bezel factor. To achieve the study objective, an experiment based on touch tasks using one-handed interaction was designed. Data on the task performance, electromyogram (EMG) activity, and subjective workload were collected to analyze the touch behavior of the participants. On the basis of the results, this study provides insights useful for designing smartphone FF.

2. Research frameworks

2.1. Research hypothesis

This study tested the following hypotheses concerning the effects of smartphone FF on touch behaviors. The first hypothesis was that increasing the smartphone width level would have a negative effect on task performance (task success rate and task completion time), subjective workload, and EMG activity during one-handed interaction. The second hypothesis was that decreasing the smartphone bottom bezel would have a negative effect on task performance, subjective workload, and EMG activity during one-handed interaction. The width was defined as the length between the left and right side of a smartphone, and bottom bezel refers to the physical area existing between the bottom of the smartphone device and the bottom of the display.

In addition, these changes in the FF impose additional physical burden on the user's hand. However, in case of a subjective workload, it was expected that physical demand, performance, and effort measures were only significant according to changes in the FF because the dimensions of mental demand, temporal demand, and frustration were not highly related to smartphone touch tasks.

2.2. Pre-experiment: investigation of NTP for one-handed interaction

Before conducting the main experiment, a pre-experiment was conducted to investigate the users' NTP when interacting with a smartphone by using one hand. The NTP refers to the point of the thumb with a natural one-handed grip. The NTP was considered because the aim was to design an experimental task that would be similar to an actual task. Smartphone users usually use tapping interactions for many situations, such as running applications, selecting pictures, and navigating menus. In these situations, users move their thumb from the NTP of the one-handed grip. Therefore, we intended to find the basic thumb position and design tapping tasks were designed based on this position.

Twenty-five participants (18 men, 7 women) were recruited for the pre-experiment. Their age was between 21 and 32 years (M = 26.8, SD = 3.72). The mean smartphone usage experience was 6.78 years (SD = 2.95). The participants were required to use smartphones for few a minutes using their hand posture in one hand. Then, they were required to run an experimental application and to tap their thumb on the screen three times. These data were used for setting the basic position of the tapping task in the main experiment session. The NTP was measured for each experimental device because the natural posture could be different depending on the device.

Table 1
Basic specifications of the experimental devices.

	Width device				Bezel device
	w67	w70	w72	w74	
Device size	145 × 67 × 8	142.4 × 69.6 × 7.9	146 × 72 × 8.1	149.4 × 73.9 × 7.3	145 × 67 × 8
Screen size	62.0 × 106.1	63.0 × 107.8	64.0 × 109.5	68.0 × 116.4	65.0 × 111.0
Weight	143 g	152 g	161 g	159 g	141 g

Note: Unit of size: mm.

3. Methods

3.1. Experimental variables and tasks

In the main experiment session, a user experiment was designed with two independent variables: width and bottom bezel. The width of smartphones in the experiment ranged from 67 to 74 mm. Specifically, four smartphones with widths of 67, 70, 72, and 74 mm were used. The bottom bezel is defined as the physical bezel area below the smartphone screen. Five levels of the bottom bezel were used: 2.5, 5, 7.5, 10, and 12.5 mm. The range of variables was selected by considering the specifications of major premium smartphones.

Three different dependent variables were collected to investigate touch behaviors. First, data on effectiveness and efficiency were collected as task performance measures. Effectiveness was measured according to the success rate, defined as the percentage of success task in a single attempt. The task completion time was collected as an efficiency measure. Second, the EMG activity of thumb muscles was measured. The first dorsal interosseous (FDI) and abductor pollicis brevis (APB) muscles were selected because these two muscles were primarily used on smartphone touch behaviors in previous studies (Kwon et al., 2016; Xiong and Muraki, 2014). Third, the subjective workload level was collected based on NASA-TLX measures (Hart, 2006). The questionnaire consisted of 21 Likert-scale items.

3.2. Experimental tasks

To investigate one-handed interaction with smartphones, a tapping task that is widely used for smartphone interaction was selected. Participants were required to touch the circled target icon as quickly and as accurately as possible. After the participants tapped the target, the next target appeared immediately.

Grid-based task has been widely used to test one-handed tapping interactions in previous studies (Park and Han, 2010; Perry and

Fig. 1. Experimental device settings for the bottom bezel conditions.

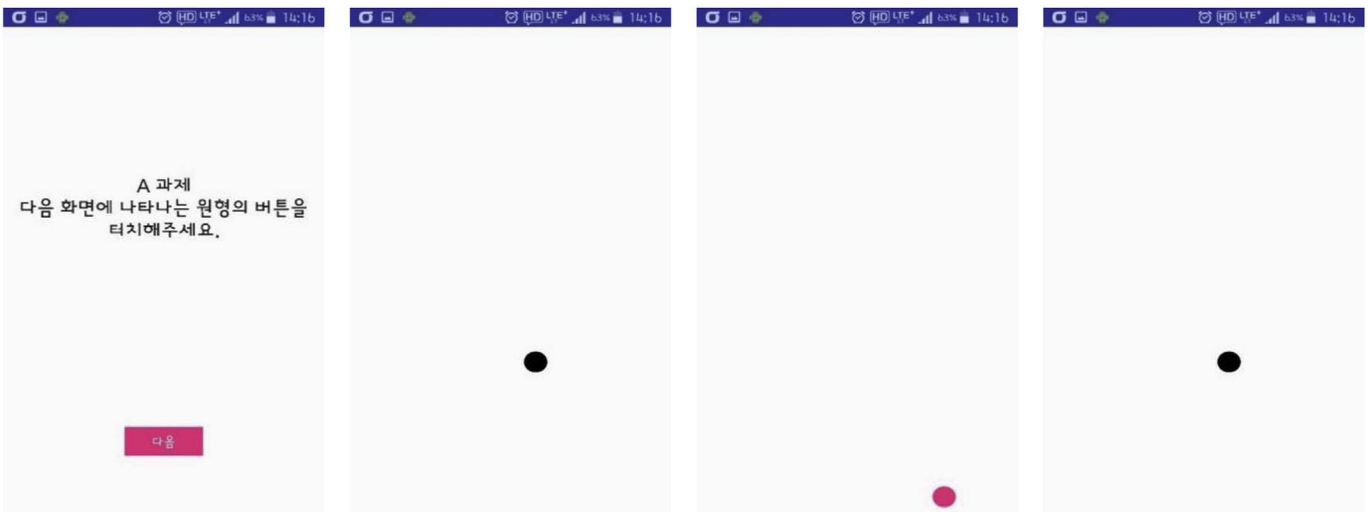

Fig. 2. Screenshots of the experimental application.

Hourcade, 2008), because this method has the advantage of presenting the touch target as the entire screen area without blank space. However, this method may not consider the actual task context. Therefore, tapping tasks were developed based on the method of Bergstrom-Lehtovirta et al. (2011). The tapping target was divided into two types, which were presented by turns. The first type was located at the NTP, and the second type was a target icon that was present on the entire screen area. The coordinates of the NTP were decided on the basis of the results of the pre-experiment. The second target type was included because the aim of the first target type was to place a thumb on the basic position during tapping tasks.

The size of the target was controlled at two levels (5 and 10 mm) to modulate the level of difficulty. These two levels were based on the widely used icon sizes for Android applications.

3.3. Apparatus and materials

Four smartphones with widths of 67, 70, 72, and 74 mm were used to investigate the effects of the width level. Table 1 shows the basic specifications of the experimental devices related to the experiment.

An action was taken to prevent contamination from factors besides the smartphone width. First, an insulation tape was applied on the top and bottom bezel areas to control the effects of the bezel, hide the brand of the smartphones, and prevent participants from touching the home button or back button. Second, the weight of the smartphones was controlled at a similar level. The difference between the heaviest device and the lightest device was less than 10%. The reason for not setting an exact same level of weight was to prevent unnatural grip and to avoid alterations in the center of gravity of the device.

Sharp Aquos 2 (131 × 67 × 10 mm; 141 g) with a 5.0-in. display was used to test the bottom bezel. The top bezel of this model is extremely thin. The experiment was conducted by using the model upside down. Then, five levels of bottom bezel that could be attached by using different heights of the insulation tape were made. Other factors were not modulated because the device used for this condition was identical, except for the bottom bezel. Fig. 1 shows the experimental devices.

An application was developed for the experiment based on the Android operating system. The application was designed to record parameters after configuring the participants' information and experimental settings. The starting page included an explanation and the start button. Experimental data were recorded after the start button was pressed. The touch target was randomly presented on the assigned coordinates. The touch target was placed at a predetermined position based on a certain distance and angle from the NTP. The center coordinates of the target are such that the distance from NTP is increased by 5 mm. At each distance, a total of 16 positions were assigned at an interval of 22.5°. Fig. 2 shows the actual application pages. The first image is the application homepage; the second image is the start page; and other images show the tapping target at different locations (Fig. 2).

3.4. Participants

Sixty-six participants (34 men, 32 women) between the ages of 19 and 39 years (M = 29.1 years, SD = 4.81) took part in the experiment. The average smartphone experience duration was 7.30 years (SD = 3.06). People who participated in the pre-experiment session were not included in the main experiment.

Participants who preferred to use their right hand for interacting

Table 2
Statistical results for width devices.

Success rate	w67	w70	w72	w74	Statistical differences
5 mm target	69.7%	64.4%	64.7%	65.3%	$p < 0.05$
10 mm target	90.6%	89.7%	89.1%	89.9%	$p = 0.731$
Overall	80.4%	77.3%	77.0%	78.0%	–
Task completion time	**w67**	**w70**	**w72**	**w74**	**Statistical differences**
5 mm target	528.89 ms	507.62 ms	513.58 ms	521.89 ms	$p < 0.05$
10 mm target	449.05 ms	436.35 ms	442.09 ms	445.65 ms	$p < 0.05$
Overall	484.14 ms	465.91 ms	472.80 ms	478.44 ms	–
NASA-TLX	**w67**	**w70**	**w72**	**w74**	**Statistical differences**
Mental demand	24.14	26.01	27.55	27.70	$p = 0.764$
Physical demand	29.89	31.59	34.51	36.35	$p < 0.05$
Temporal demand	23.13	24.29	25.93	26.67	$p = 0.380$
Performance	37.50	30.63	37.19	41.25	$p = 0.290$
Effort	31.27	34.12	37.12	38.80	$p < 0.05$
Frustration	20.73	23.35	24.98	25.88	$p = 0.148$
EMG	**w67**	**w70**	**w72**	**w74**	**Statistical differences**
%RVC of FDI	30.5	33.0	35.4	35.3	$p = 0.636$
%RVC of APB	15.8	16.8	15.5	16.9	$p = 0.964$

Note. Statistical differences were from the results of ANOVA tests.
RVC, reference voluntary contraction.

with the smartphone were included. Fifty-seven participants were right-handed, and the others were ambidextrous. The average hand length was 192.31 mm (SD = 8.37) for men and 170.97 mm (SD = 9.17) for women; the average palm width was 91.66 mm (SD = 5.57) for men and 77.10 mm (SD = 4.29) for women; and the average thumb length was 65.74 mm (SD = 5.30) for men and 59.22 mm (SD = 4.39) for women.

3.5. Procedure

The objectives of the experiment and procedure were explained after welcoming the participants. All participants agreed to take part in the experiment after they had listened to the explanation. Demographic information of the participants was collected, and their hand sizes were measured. Next, the EMG device was attached to the participants' right arm and electrodes were attached to the target thumb muscles. After the muscle signal was checked, the reference level of the thumb muscles was measured. The devices were presented to the participants in different orders to prevent learning effects. Half of the participants took part in the width variable condition first, and the other half took part in the bezel variable condition first. The preset order of devices for each condition was determined by random number sampling. A break time of about 10 min was provided in the middle of experiment, and participants were able to take a break if they wanted. The participants responded to the questionnaire about the subjective workload after completing the tasks with each device.

3.6. Data collection and analysis

Task performance data were recorded by the experimental application itself. A task was considered a success if the coordinates of the tapping point were positioned inside the target circle. Based on this, every touch point was categorized as either success, fail, or success after fail. The success after fail cases were excluded from calculation of the success rate. The task completion time of successful trials was measured by subtracting the time of the previous trial from the time of the present trial. Only success cases were used in the analysis of the task completion time.

The muscle activity of the thumb was measured by using EMG device (two-channel Shimmer3 EMG unit; SHIMMER Research, Dublin, Ireland). The EMG electrodes were attached to two muscles of the thumb, namely the FDI and APB. The sampling rate of the EMG signal was 512 Hz, and a 20–250 Hz band-pass filter was applied. After the

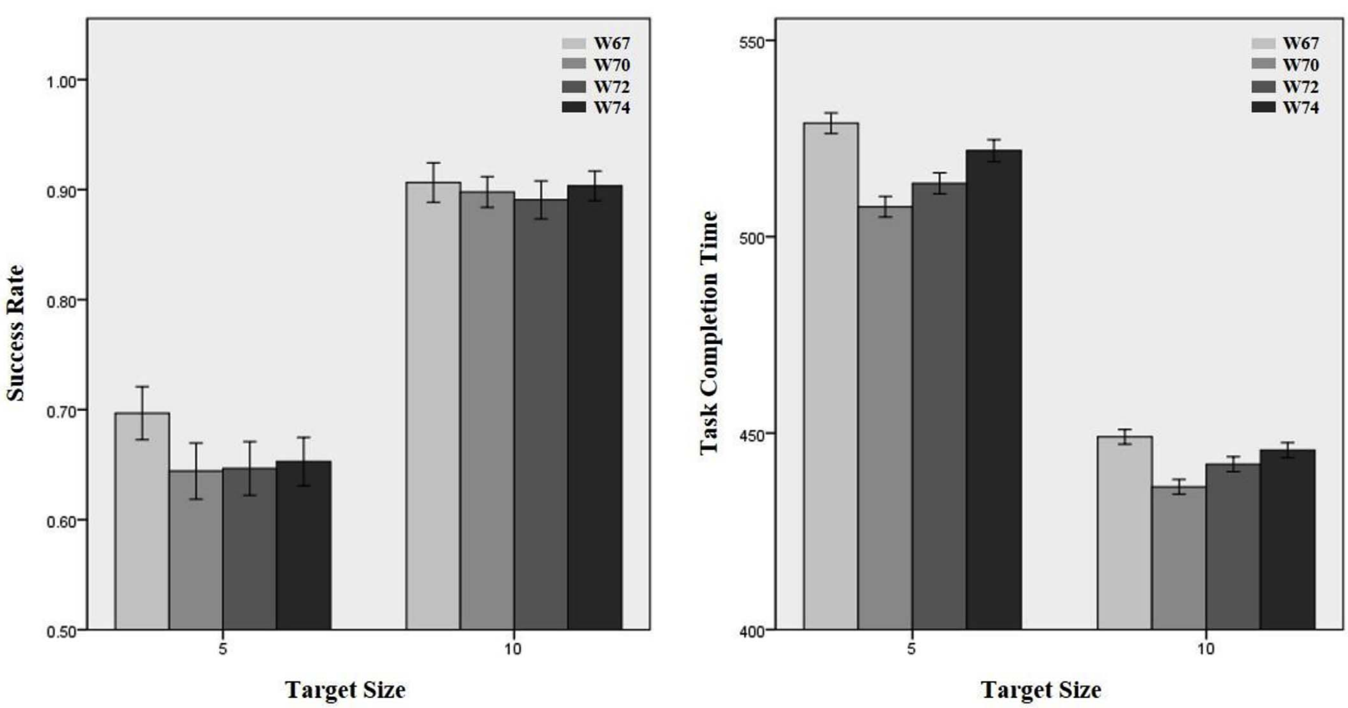

Fig. 3. Task performances on width devices.

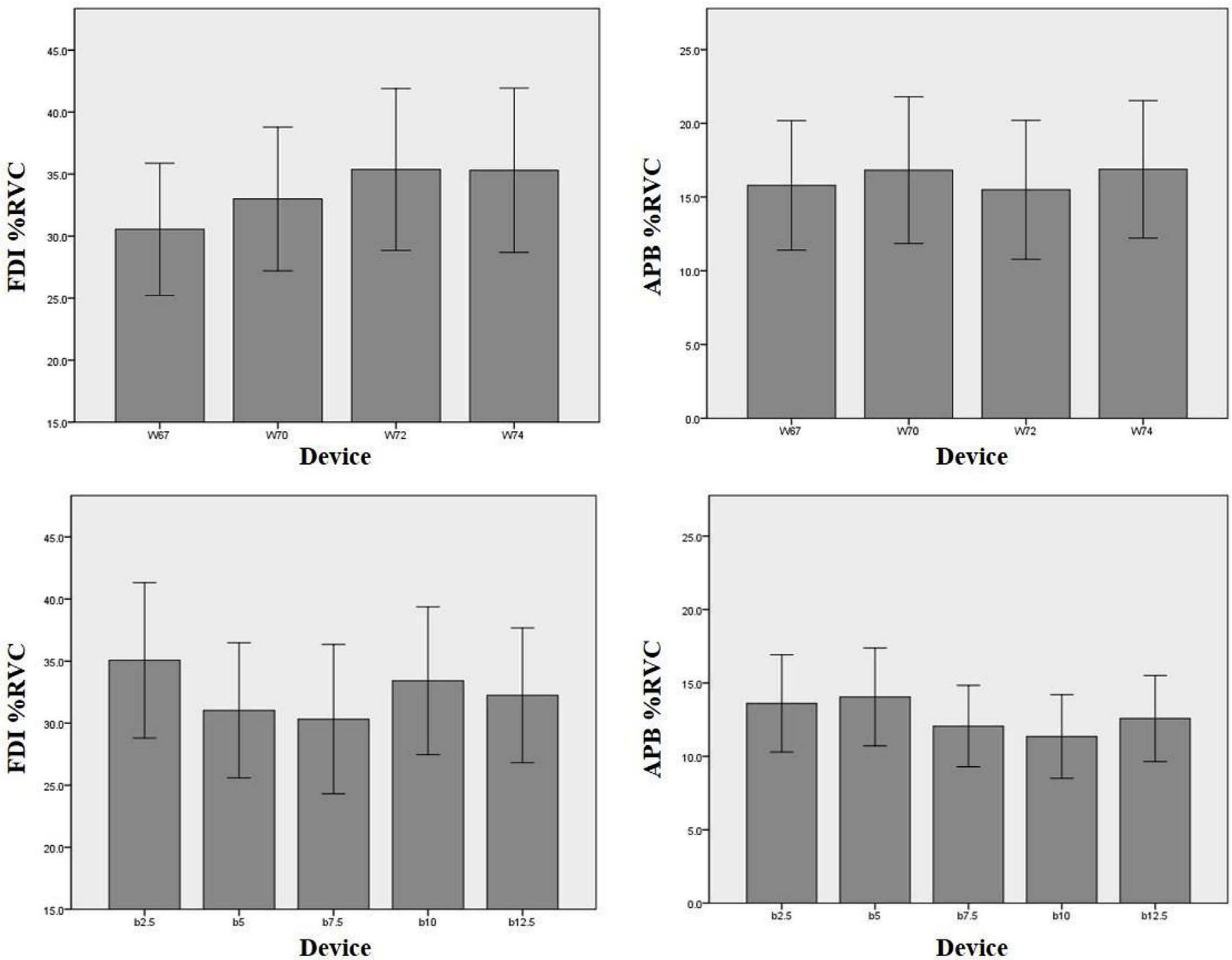

Fig. 4. EMG results for width and bezel devices.

application of the band-pass filter, raw data were calculated by using the root mean square (RMS) method. Data were normalized by dividing the RMS data by the reference voluntary contraction.

The paper-based NASA-TLX method was used to measure the subjective workload of the tapping tasks. Participants were required to respond to the questionnaire items after completing tasks on each device. The questionnaire consisted of 21 Likert-scale items, from 0 to 100 in increments of 5. A high score on an item was designated to mean a high workload.

Statistical analyses were performed by using IBM SPSS Statistics version 23.0. The significance criterion was 0.05 for all analyses. Post-hoc analyses were performed based on Scheffe's method. Error bars in the figure represents the standard error of the mean value.

4. Results

4.1. Pre-experiment results

People who participated in the pre-experiment were required to tap the basic position of the thumb after a quick interaction with one hand. A total of 75 data points were collected for every device of the experiment. The size of the screen was measured, and the mean values of the x and y coordinates on the screen were calculated for each device. The coordinates of the bottom right corner of the screen were the local origin (0, 0), and the units were millimeters. The NTP coordinates for the 67, 70, 72, and 74 mm devices were (29.9, 40.4), (30.1, 35.7), (30.4, 38.0), and (33.2, 39.0), respectively. The coordinates for the bezel device were (30.8, 44.5).

4.2. Effects of width level on task performance, subjective workload, and EMG activity

Task performance. Table 2 shows the descriptive statistics of the task performances. There were differences among devices in the 5 mm target size condition but not in the 10 mm target size condition. Therefore, a two-way analysis of variance (ANOVA) was conducted to determine the effects of width and task difficulty on the success rate. The results showed that the main effects were significant, but the interaction effect did not significantly affect the success rate [width: $F\,(3, 1005) = 4.26$, $p < 0.05$; task difficulty: $F\,(1, 1005) = 14.51$; $p < 0.05$, width × task difficulty: $F\,(3, 1005) = 1.94$, $p = 0.122$]. The results of the post-hoc test revealed that the success rate of the w67 (width 67 mm) device was significantly higher than that of the other devices. A two-way ANOVA with Scheffe's post-hoc test was also conducted. The results of the task completion time showed that the main effects and interaction effect were significant [width: $F\,(1,1005) = 82.306$, $p < 0.05$; task difficulty: $F\,(1, 1005) = 84.243$, $p < 0.05$; width × task difficulty: $F\,(3, 1005) = 6.47$, $p < 0.05$]. The results of the post-hoc test indicated that the task completion time of the w67 device was the longest, followed by that of the w74, w72, and w70 devices. Fig. 3 shows the effects of width

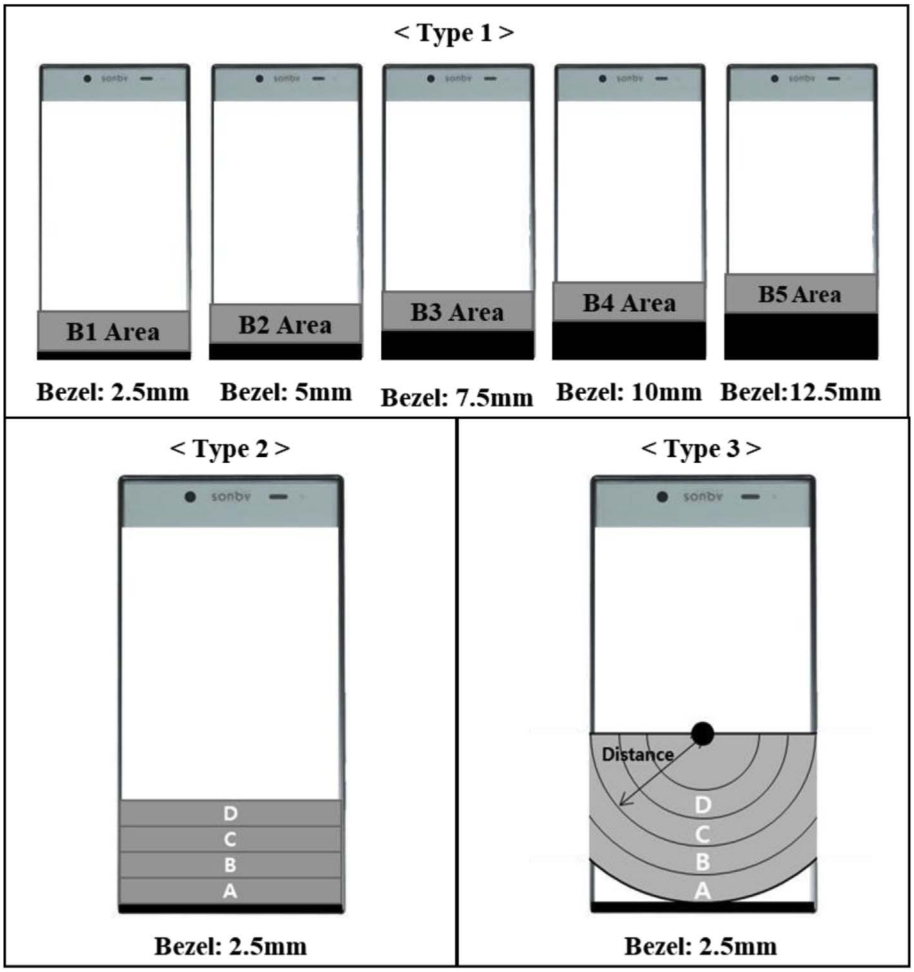

Fig. 5. Three types of evaluation criteria for analyzing task performances in bottom bezel conditions.

and difficulty on task performances. All error bars in the figure are based on a confidence interval of 0.95.

Subjective workload. Data from seven participants were excluded because of poor data quality. Three of the participants responded to most questionnaire items by using 0 or 100, and four participants had the wrong box checked for the questionnaire items; these were not recognized during the experimental process. Therefore, data from 59 participants were included in the analysis of subjective workload.

The average score of the NASA-TLX results is presented in Table 2. The task difficulty showed a significant effect on all measures (the result of performance was marginally significant; $p < 0.69$). However, differences according to width level were found only in physical demand ($p < 0.05$) and effort ($p < 0.05$).

EMG. The signals of the FDI and APB muscles of the thumb were analyzed. The average usage of the FDI ranged from 30% to 40%, and that of the APB ranged from 10% to 20% (Table 2). Although the average usage of muscles increased with increasing width level, significant differences were not found by ANOVA tests (Fig. 4).

4.3. Effects of bottom bezel on task performance, subjective workload, and EMG activity

Task performance. Three different evaluation criteria were applied to analyze the effects of bottom bezel on task performance, as shown in Fig. 5. The first criterion (type 1) analyzed was the 10 mm touch area at the bottom of the screen among devices with different bottom bezels (Fig. 5, upper). Most smartphones utilize this area for frequently used applications. Accordingly, it is important for users to be able to easily tap the icon within this touch area. The results indicated a significant difference in the success rate among the touch areas of the devices, as analyzed by using one-way ANOVA [$F(5, 999) = 36.17$, $p < 0.05$]. The results of the task completion time were similar to those of the success rate. A one-way ANOVA with post-hoc analysis also showed differences among devices [$F(5,999) = 73.99$, $p < 0.05$]. The lowercase letters in Fig. 6 indicate the same groups of performance based on the post-hoc analysis.

The other two methods analyzed the touch area below the NTP. The second type analyzed the performance of the divided touch area according to position (Fig. 5, lower left). The touch area was divided into four regions: A from 0 to 10 mm, B from 10 to 20 mm, C from 20 to 30 mm, and D from 30 to 40 mm in type 2 criterion. A significant difference was found in the success rate [$F(4, 1000) = 49.63$, $p < 0.05$] and task completion time [$F(4, 1000) = 121.13$, $p < 0.05$] among touch areas based on the results of one-way ANOVA. A post-hoc test indicated that the touch areas of C and D resulted in the highest performance, followed by those of B and A.

The third criterion (type 3) evaluated touch areas radially from the NTP (Fig. 5, lower right). The touch area was divided into four regions according to the distance from the NTP: A from 35 to 45 mm, B from 25 to 35 mm, C from 15 to 25 mm, and D from 5 to 15 mm. It was confirmed that there were significant differences among the touch areas related to not only the success rate [$F(4, 1000) = 63.72$, $p < 0.05$] but also the task completion time [$F(4, 1000) = 274.22$, $p < 0.05$]. The results of the post-hoc analysis indicated that the participants performed the tasks better in the touch areas of C and D, followed by those of B and A.

Subjective workload. The results of the NASA-TLX survey for the bezel devices were not significant. The task performances related to the

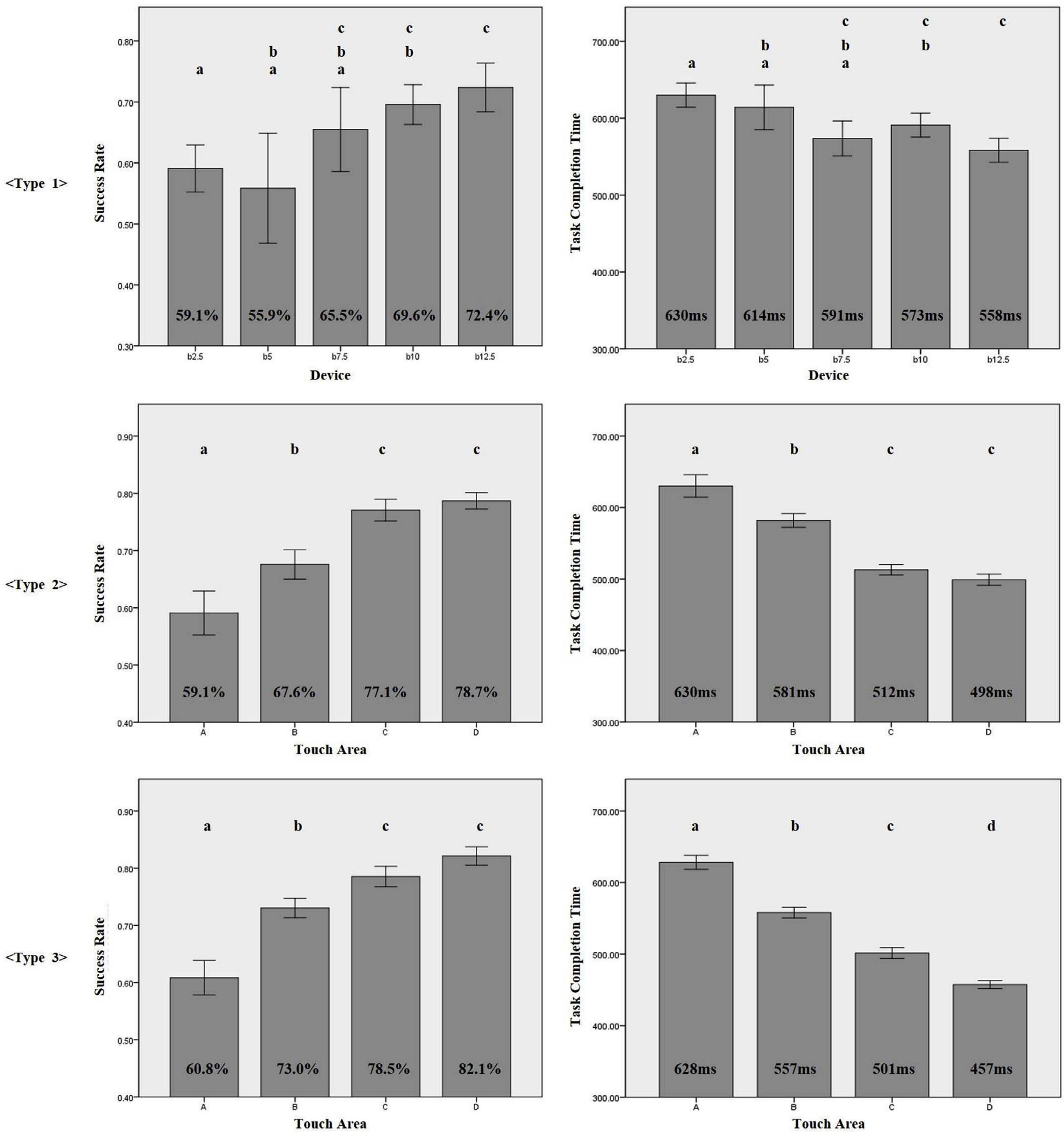

Fig. 6. Task performances on bezel device conditions.

bottom touch area below the NTP were analyzed. However, the participants were informed that the touch targets covered the entire touch area of the screen in order to prevent their prediction of a target location. Accordingly, the participants might not have perceived the differences among the five devices for testing the bezel levels.

EMG. The EMG data showed no differences among different bottom bezel levels. The average usage of the FDI for the 2.5, 5, 7.5, 10, and 12.5 mm conditions was 35.4%, 33.2%, 31.1%, 33.5%, and 32.7%, respectively. The average usage of the APB for the 2.5, 5, 7.5, 10, and 12.5 mm conditions was 13.5%, 14.2%, 11.9%, 11.4%, and 11.5%, respectively. A one-way ANOVA test showed that there were no differences for the conditions ($p = 0.124$).

5. Discussion and conclusions

This study examined the effects of smartphone FF, namely width and bottom bezel, on tapping task performances, EMG activity, and subjective workload. A pre-experiment was conducted to determine the NTP for the actual tapping task context. On the basis of the data obtained from the pre-experiment, one-handed tapping tasks were conducted to test the width and bottom bezel of smartphone FF.

Most results supported the hypotheses. At first, significant

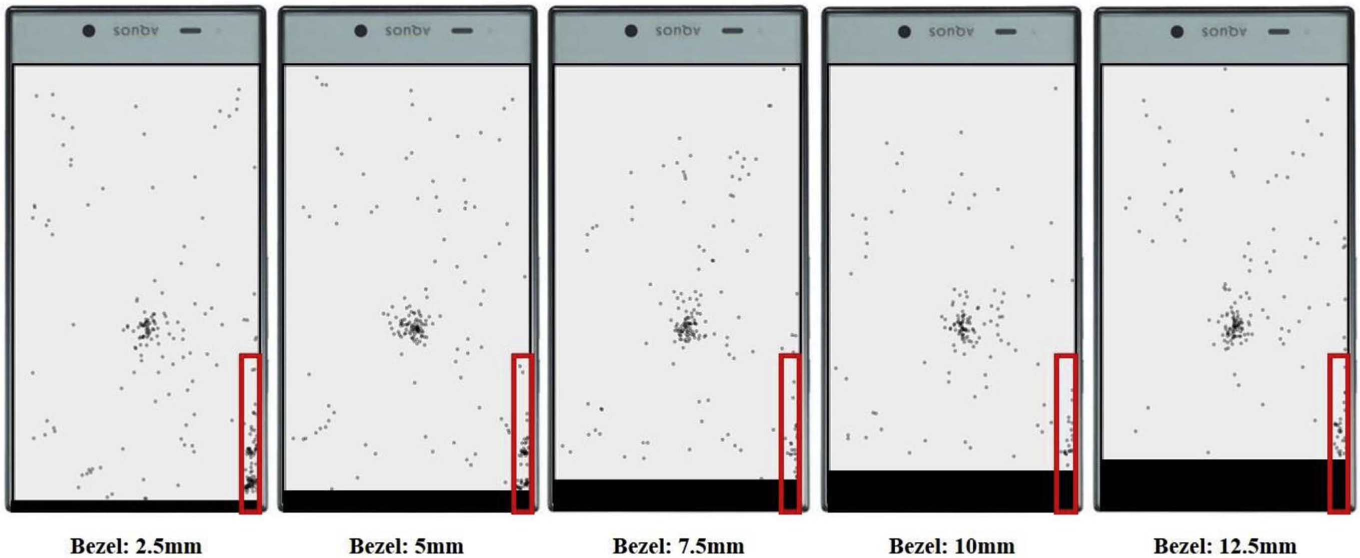

Fig. 7. Error touch cases at more than 30 mm from the target position.

differences were found by ANOVA tests for the device width and task difficulty factors. The results of the effects of the target size are in line with those of previous studies (Hwangbo et al., 2013; Parhi et al., 2006; Park and Han, 2010). Specifically, no differences in the success rate were found in the 10 mm target size condition. However, the success rate of the 67 mm device was better than those of other devices in the 5 mm target size condition. Interestingly, the results of the task completion time did not show identical patterns with the success rate. The task completion time increased with increasing width level. In other words, task efficacy was impaired as the width level increased. However, the task completion time of the 67 mm device was higher than that of other devices without reference to task difficulty. Thus, it can be concluded that task efficiency improved with decreasing device size, in general; however, this does not mean that smaller devices were better. That is, if the size of the device decreases below a particular level, then task efficiency would be impaired.

It was expected that there would be significant differences among devices related to three workload dimensions, namely physical demand, performance, and effort. However, the results of only two measures (physical demand and effort) differed significantly based on the width size. Nevertheless, the results of the subjective workload indicated similar patterns with that of the task performance. The participants felt that larger devices required more effort and physical demands to perform the tasks, except for the 67 mm condition. It was identified that the task efficiency of the 67 mm device was poorer than that of the other devices. The participants responded that more effort was required to perform tasks with the 67 mm device.

The EMG data did not statistically support the expected results because of the characteristics of the muscle signals, which vary widely in different people. In fact, deviations of the muscle signal in previous studies also showed artificially high standard deviations (Chiu et al., 2015; Kim et al., 2014; Pereira et al., 2012). Although the differences were not statistically significant, the average difference in muscle usage between the 67 and 74 mm devices was about 3%. These differences have important meanings considering that the participants performed the tasks in a relatively short time. The physical demand on the hand or finger might have increased as users spent more time with the smartphones. Considering that many people use smartphones for extended periods, these differences lead to critical issues.

The effects of bottom bezel on touch behavior were analyzed by using three other frameworks. The differences in the task performances of the 10 mm touch area from the bottom screen based on the device were observed first. The participants succeeded in performing the tapping task on about 70% of the trials at the 10 and 12.5 mm bezel conditions. However, the success rate dropped to 65% at the 7.5 mm condition and below 60% at the 5 and 2.5 mm conditions. The patterns of task completion time were similar to the results of the success rate. The results from the other two frameworks were also similar. It was found that the task performances of the touch area within 20 mm of the bottom bezel were worse than those of the touch area over 20 mm. It was also observed that the results from the last framework were similar to other results. The task performances gradually decreased with increasing distance from the NTP.

There were no significant differences in the EMG results for different bottom bezel devices. These results could originate from the experimental design in that the touch targets were present on the whole screen to prevent learning effects. Although differences of bottom bezel ranging from 2.5 to 12.5 mm influenced the touch performance, the thumb movements did not considerably differ among devices. Accordingly, the bottom bezel levels did not seem to make a significant difference. The evaluations of subjective workload were not significant, which was contrary to expectations. As mentioned before, it was suspected that this occurred because it was difficult to perceive the differences among devices.

To scrutinize the touch behavior for different bottom bezel levels, the touch area points were analyzed. Fig. 7 shows the touch error cases at positions more than 30 mm from the target point. The touch points in the red box could be considered a result of palm touch. Palm touch errors were observed more frequently in the smaller bezel conditions. Thus, a smaller bezel led to palm touch errors, thereby changing touch behaviors. To avoid palm touch error, the participants tried to tap the target with an unnatural hand grip. This unnatural grip led to increased physical demands on the thumb and to increased task completion time. Similar results patterns were observed in the second and third methods. The task performance, success rate, and task completion time decreased as the target points moved farther from the basic NTP.

Although not all of the results agreed with the expectations, most results were as expected. Importantly, increasing the screen-to-body ratio led to usability issues. The results showed that usability issues should be considered a trade-off issue based on increasing screen-to-body ratios.

In summary, this study investigated the effects of smartphone FF on one-handed interaction, providing insights for studying smartphones from the perspective of ergonomics and human–computer interactions. These results could contribute to the design of smartphone hardware FF. Furthermore, the experimental approaches used here would be helpful for studying future smartphone FF.

There are several issues that were not completely controlled in this study. First, only tapping tasks were considered as a one-handed interaction. Today, various touch gestures are used for interacting with smartphones such as double tap, drag, flick, pinch zoom, and rotate. Research on these gestures would be helpful to understand user touch behaviors. Second, this study only included participants aged between 19 and 39 years. As these age groups are more familiar with smartphones than older age groups, a future study should examine the touch behaviors of older participants. Third, factors other than the experimental variables could not be controlled to the same level because actual smartphones were used as the experimental device. Therefore, there could be subtle physical differences depending on the device.

References

Bergstrom-Lehtovirta, J., Oulasvirta, A., Brewster, S., 2011. The effects of walking speed on target acquisition on a touchscreen interface. In: Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services - MobileHCI '11. ACM Press, New York, New York, USA, pp. 143. https://doi.org/10.1145/2037373.2037396.

Chiang, Z.H., Wen, C.C., Chen, A.C., Hou, C.Y., 2013. An analysis of smartphone size regarding operating performance. In: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 8017 LNCS(PART 2), pp. 363–372. https://doi.org/10.1007/978-3-642-39215-3_43.

Chiu, H.-P., Tu, C.-N., Wu, S.-K., Chien-Hsiou, L., 2015. Muscle activity and comfort perception on neck, shoulder, and forearm while using a tablet computer at various tilt angles. Int. J. Hum. Comput. Interact. 31 (11), 769–776. https://doi.org/10.1080/10447318.2015.1064639.

Hart, S.G., 2006. Nasa-task load index (NASA-TLX); 20 Years later. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 50 (9), 904–908. https://doi.org/10.1177/154193120605000909.

Hwangbo, H., Yoon, S.H., Jin, B.S., Han, Y.S., Ji, Y.G., 2013. A study of pointing performance of elderly users on smartphones. Int. J. Hum. Comput. Interact. 29 (9), 604–618. https://doi.org/10.1080/10447318.2012.729996.

Kietrys, D.M., Gerg, M.J., Dropkin, J., Gold, J.E., 2015. Mobile input device type, texting style and screen size influence upper extremity and trapezius muscle activity, and cervical posture while texting. Appl. Ergon. 50, 98–104. https://doi.org/10.1016/j.apergo.2015.03.003.

Kim, J.H., Aulck, L., Thamsuwan, O., Bartha, M.C., Johnson, P.W., 2014. The effect of key size of touch screen virtual keyboards on productivity, usability, and typing biomechanics. Hum. Factors J. Hum. Factors Ergon. Soc 0018720814531784-. https://doi.org/10.1177/0018720814531784.

Kwon, S., Bahn, S., Ahn, S.H., Lee, Y., Yun, M.H., 2016. A study on the relationships among hand muscles and form factors of large-screen curved mobile devices. Int. J. Ind. Ergon. 56, 17–24. https://doi.org/10.1016/j.ergon.2016.07.003.

Lin, M., Goldman, R., Price, K.J., Sears, A., Jacko, J., 2007. How do people tap when walking? An empirical investigation of nomadic data entry. Int. J. Hum. Comput. Stud. 65 (9), 759–769. https://doi.org/10.1016/j.ijhcs.2007.04.001.

Nick, T., 2012. Smartphone Displays Need a Bezel. Here's Why. Phone Arena. http://www.phonearena.com/news/Smartphone-displays-need-a-bezel.-Heres-why_id27670.

Oehl, M., Sutter, C., Ziefle, M., 2007. Considerations on efficient touch interfaces - how display size influences the performance in an applied pointing task. Hum. Interface Manag. Inf. Methods, Tech. Tools Inf. Des. 4557, 136–143. https://doi.org/10.1007/978-3-540-73345-4.

Parhi, P., Karlson, A.K., Bederson, B.B., 2006. Target size study for one-handed thumb use on small touchscreen devices. In: Proceedings of the 8th Conference on Human-computer Interaction with Mobile Devices and Services - MobileHCI '06, vol. 203. https://doi.org/10.1145/1152215.1152260.

Park, Y.S., Han, S.H., 2010. Touch key design for one-handed thumb interaction with a mobile phone: effects of touch key size and touch key location. Int. J. Ind. Ergon. 40 (1), 68–76. https://doi.org/10.1016/j.ergon.2009.08.002.

Pereira, A., Lee, D.L., Sadeeshkumar, H., Laroche, C., Odell, D., Rempel, D., 2012. The effect of keyboard key spacing on productivity, usability, and biomechanics in touch typists with large hands. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 56 (1), 1872–1876. https://doi.org/10.1177/1071181312561271.

Pereira, A., Miller, T., Huang, Y.-M., Odell, D., Rempel, D., 2013. Holding a tablet computer with one hand: effect of tablet design features on biomechanics and subjective usability among users with small hands. Ergonomics 56 (9), 1363–1375. https://doi.org/10.1080/00140139.2013.820844.

Perry, K., Hourcade, J., 2008. Evaluating one handed thumb tapping on mobile touchscreen devices. Proc. Graph. Interface 2008, 57–64. Retrieved from. http://dl.acm.org/citation.cfm?id=1375725.

Petrovan, B., 2015. Infographic: the phones with the highest and lowest screen-to-body ratios. http://www.androidauthority.com/phones-highest-lowest-screen-to-body-ratios-610915.

Steven, H., 2013. How Do Users Really Hold Mobile Devices? http://www.uxmatters.com/mt/archives/2013/02/how-do-users-really-hold-mobile-devices.php.

Trudeau, M.B., Asakawa, D.S., Jindrich, D.L., Dennerlein, J.T., 2016. Two-handed grip on a mobile phone affords greater thumb motor performance, decreased variability, and a more extended thumb posture than a one-handed grip. Appl. Ergon. 52, 24–28. https://doi.org/10.1016/j.apergo.2015.06.025.

Victor, H., 2014. Did You Know that Smartphone Screens Nearly Doubled in Size since 2007. Phone Arena. http://www.phonearena.com/news/Did-you-know-that-smartphone-screens-nearly-doubled-in-size-since-2007_id52067.

Xiong, J., Muraki, S., 2014. An ergonomics study of thumb movements on smartphone touch screen. Ergonomics Taylor & Francis. https://doi.org/10.1080/00140139.2014.904007.

Xiong, J., Muraki, S., 2016. Effects of age, thumb length and screen size on thumb movement coverage on smartphone touchscreens. Int. J. Ind. Ergon. 53, 140–148. https://doi.org/10.1016/j.ergon.2015.11.004.