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Investigating Smartphone Touch Area with One-Handed Interaction: Effects of Target Distance and Direction on Touch Behaviors

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ABSTRACT
The objective of this study was to investigate the touch area that can be comfortably reached by the thumb during one-handed smartphone interaction. To achieve the research objective, we introduced the concept of natural thumb position when designing a tapping task and conducted an user experiment. The independent variables were the target distance and direction from the natural thumb position, and the three dependent variables were the task performance, information throughput, and touch accuracy. The results showed that participants performed the task comfortably in the diagonal direction between the upper right and the lower left side of the screen. The task performance deteriorated as the target distance increased, especially at 45 mm or more. The touch accuracy was measured using X- and Y-coordinates data. Participants touched the left side of the target center, except near the proximal area of the hand. They also touched the points above the center of the target in the upper screen area and points below the center of the target in the lower screen area. The findings of this study provided insights for designing a smartphone touch interface considering the comfortable touch areas of one-handed interaction.

1. Introduction

1.1. Background

The touch interface is one of the factors behind the success of the smartphone because it acts as a tool for inputting and outputting information simultaneously (Scott & Conzola, 1997). Recently, the screen size of smartphones has gradually increased because users expect to use smartphones for multiple purposes. Although a larger smartphone may be a reflection of users' needs, it is doubtful whether this change is desirable from the perspective of human–computer interaction (HCI). Correspondingly, there has been an increase in the size of uncomfortable touch areas experienced during one-handed device interaction (Xiong & Muraki, 2016). Considering one-handed touch is the preferred interaction method, this usability issue should be investigated. Various attempts have been made to resolve this issue. Smartphone manufacturers are introducing a one-handed mode that shrinks the active area of the screen and moves it to the bottom right corner to allow easier access, as shown in Figure 1. In addition, some researchers have attempted to provide novel one-handed thumb interaction techniques (Bonnet, Appert, & Beaudouin-Lafon, 2013; Hoggan, Brewster, & Johnston, 2008; Lai & Zhang, 2015). However, in addition to not resolving the fundamental usability issues, these approaches are difficult to adopt universally for all products. Therefore, it is necessary to investigate the comfortable touch area for smartphone users.

Accordingly, numerous studies have focused on evaluating the touch behaviors of one-handed interaction (Cha, Hwangbo, Lee, & Ji, 2017; Hwangbo, Yoon, Jin, Han, & Ji, 2013; Im, Kim, & Jung, 2015; Keller, Swaminathan, & Sireci, 2003; Lee, Cha, Hwangbo, Mo, & Ji, 2018; Ng, Brewster, & Williamson, 2014; Park & Han, 2010a, 2010b; Perry & Hourcade, 2008; Roig-Maimó, MacKenzie, Manresa-Yee, & Varona, 2017). Many researchers have investigated the touch area of a smartphone by dividing the screen into sections using a grid. Perry and Hourcade (2008) tested the touch area using a personal digital assistant (PDA) device with a diagonal screen size of 3.5 in. They conducted a tapping task that included five target sizes and 25 positions based on Fitts' law. The results of this study revealed that the edge of the screen area showed a higher performance than the central area. However, the findings of Park and Han (2010b) were inconsistent with those of Perry and Hourcade (2008). Park and Han (2010b) conducted a tapping task to investigate the effects of touch key size and location when participants interacted with a mobile device using one-handed thumb interaction. They divided the screen into 25 locations, and these locations were used to provide a target touch key. The task performances for the central area or left side of the screen were relatively better than those for other areas. Park and Han (2010b) concluded that these differences may have resulted from thumb movement distance axnd

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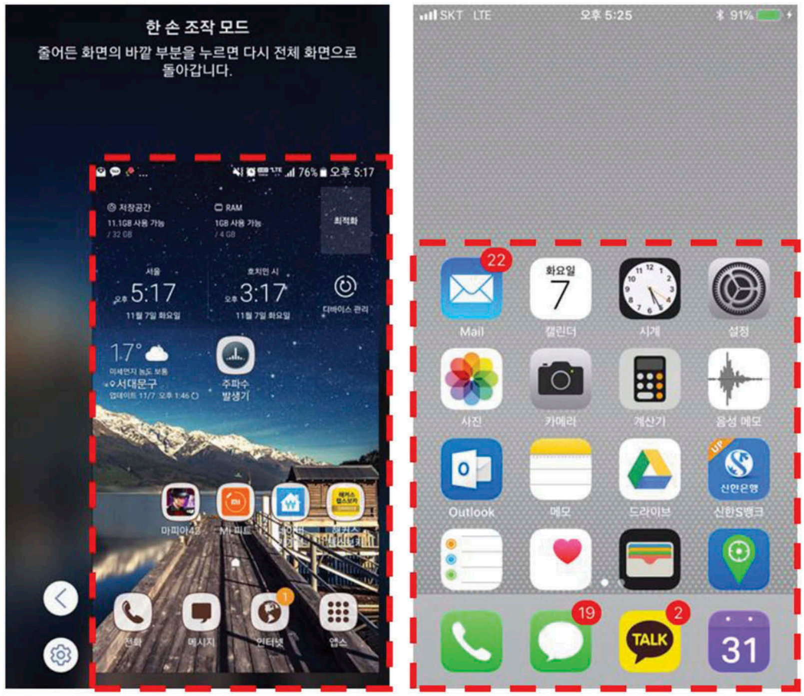

Figure 1. One-handed mode display on premium smartphones (left: Samsung Galaxy 8, right: Apple iPhone 7).

direction. In an experiment by Perry and Hourcade (2008), the thumb movement distance and direction were the same across all of the task trials; however, Park and Han (2010b) did not control these variables at the same levels. Other studies also supported the findings of Park and Han (2010b) (Hwangbo et al., 2013; Ng et al., 2014; Trudeau, Young, Jindrich, & Dennerlein, 2012).

Although the findings of the above reviewed studies provided meaningful insights for understanding the touch area on a smartphone screen, there were some limitations. First, considering the size of recent premium smartphones, the device and screen sizes of the smartphones used in the prior studies were relatively small. It is questionable whether the findings of these studies using smaller devices could explain the behaviors of users interacting with larger devices. Second, there were inconsistent results among several studies using a grid-based touch task paradigm. In this respect, it can be seen that the existing studies provided insufficient results for understanding the touch behaviors of smartphone users. Further, other studies have also pointed out these issues. For example, Bergstrom-Lehtovirta and Oulasvirta (2014) proposed a mathematical model for predicting the functional area of the thumb movement on a touch screen, arguing that a grid-based approach has limitations. Xiong and Muraki (2016) pointed out that the rate of increase in thumb movement coverage was smaller than the increase in screen size.

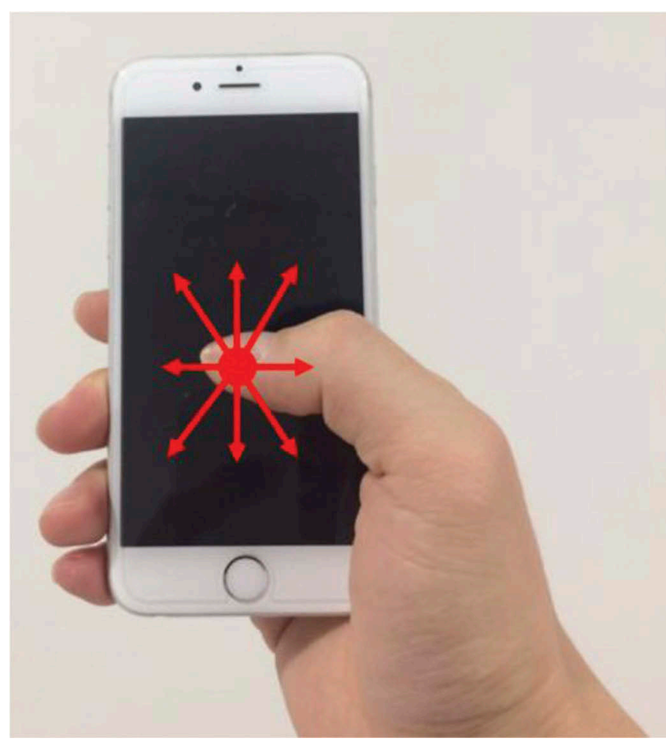

Figure 2. Natural postures of one-handed interaction.

1.2. Factors influencing touch behaviors during smartphone interaction

One-handed interaction is one of the preferred methods of interacting with smartphones. In one-handed interaction, users usually hold the device and place their thumb in a natural position, as shown in Figure 2. Based on this posture, they move their thumb to perform tasks such as tapping and dragging. In this study, we considered tapping as a representative task to investigate touch behaviors. To perform a tapping task, the distance and direction that the thumb was moved were determined by the position of the target icon, and the touch performances were affected by these variables

(Kim & Jo, 2015; Park & Han, 2010b; Trudeau, Udtamadilok, Karlson, & Dennerlein, 2012). Therefore, to investigate one-handed interaction with a smartphone, the target distance and direction from the natural thumb position should be considered as variables.

The target distance is a major factor when investigating touch behavior in one-handed interaction; hence, numerous researchers considered it to be a primary variable when investigating touch behaviors (Andersen, 2005; Bi, Li, & Zhai, 2013; Chang, Choi, Tjolleng, & Jung, 2017; Goncalves et al., 2017; Kim & Jo, 2015; MacKenzie, 2015; Roig-Maimó et al., 2017; Schofield, Dunagan, & Schofield, 2016; Trudeau, Udtamadilok, et al., 2012). Therefore, the target distance from the natural thumb position can also be expected to have an effect on one-handed interaction.

The target direction has also been considered to be a significant variable when users perform a touch task using their thumb in ergonomic studies of thumb movement (Kwon, Bahn, Ahn, Lee, & Yun, 2016; Trudeau, Udtamadilok, et al., 2012), as well as in usability evaluation studies of the touch area (Karlson, 2008; Kim & Jo, 2015; Montague, Hanson, & Cobley, 2012; Ng et al., 2014; Park & Han, 2010a, 2010b). For example, Trudeau, Udtamadilok, et al. (2012) tested the variations in thumb motor performance according to movement orientation, direction, and device size during one-handed interaction with a mobile phone. They developed four prototypes consisting of physical buttons, and a thumb tapping task experiment was conducted. The performance measures, which included throughput, movement time, and precision, had higher values in the distal direction of the hand than in the proximal direction. Chang et al. (2017) examined the physical demand on participants when they held a tablet PC. They used a two-thumb tapping task to evaluate the effect of button positions placed in five rows and five columns. It was confirmed that the physical demand on both hands increased when the touch target appeared in the lower screen area and at the side farthest away from the hand. Ng et al. (2014) tested target acquisition behaviors when participants walked while holding an encumbrance. They used nine target positions. When using the right hand, the touch accuracy was lower when the target was above the center position than when it was below, and it was lower when the target was on the left side from the center position than on the right side. Montague et al. (2012) compared the touch performance between direct touch interactions and developed adaptive interaction methods. Although the task error rate of the developed interface was lower than that of a direct touch interface, the results showed that the task error rate was very high in the top and left-side areas. Further, studies have reported that people had difficulty performing a touch behavior on the bottom right corner screen compared to the bottom left corner or top right corner, in terms of thumb motor performance (Trudeau, Young, et al., 2012), perceived effort (Karlson, 2008), and task errors (Park & Han, 2010b). In summary, based on right hand interaction, users felt more comfortable when they moved the thumb between the top right area and bottom left area compared to movement between the top left area and bottom right area from an ergonomic point of view. In addition, the results of a usability evaluation showed that users had difficulty performing a touch task at the bottom right corner and top left corner.

1.3. Research objective

The objective of this study was to investigate the touch area of smartphones during one-handed interaction. To achieve this research objective, we introduced the concept of natural thumb position and designed a user experiment using tapping tasks based on two independent variables (target distance and direction). Data for three types of dependent variables (touch performance, information throughput, and touch accuracy) were collected to examine the touch behaviors. The comfortable touch area was found by analyzing the experimental data. The rest of this article is organized as follows. First, we propose a research framework to overcome the limitations of previous studies on the touch area of a smartphone during one-handed interaction, and explain how we conducted a user experiment within the research framework. Next, we present the results for the touch behaviors using task performance, information throughput, and touch accuracy. Finally, we provide a discussion and conclusion.

2. Methodology

2.1. Research hypothesis

Our goal was to investigate touch behaviors during one-handed interaction. Therefore, we conducted research based on the following hypotheses on users' touch behaviors according to two independent variables. First, increasing the target distance from the natural thumb position would affect touch performance. It was a somewhat natural prediction that users would have difficulty performing touch tasks as the target moved farther away from their natural thumb position. However, our goal was to explore the points where the touch behaviors began to deteriorate. Second, it was expected that users would perform touch tasks more easily in the diagonal thumb movement area between the upper right area and lower left area compared to other areas. We investigated whether users' touch performances would differ according to the target direction from the natural thumb position. Third, it was expected that there would be interaction effects between the target distance and direction. Even though the target was positioned at the same distance, there would be different task performances according to the target direction. Fourth, it was expected that these changes in task performances could be explained by the touch accuracy data. Accordingly, touch accuracy would differ considering target distance and direction.

2.2. Experimental design

First, a pilot test was conducted to determine the natural thumb position before conducting the main experiment. Totally, 25 participants took part in the pilot test. During this session, participants freely used smartphones about 5 minutes using one-handed interaction. After they became familiar with the smartphones, they were required to run an experimental application and touch their thumb three times on the screen in a comfortable hand posture. This process was conducted for each device because the natural thumb position could differ according to the characteristics of different devices.

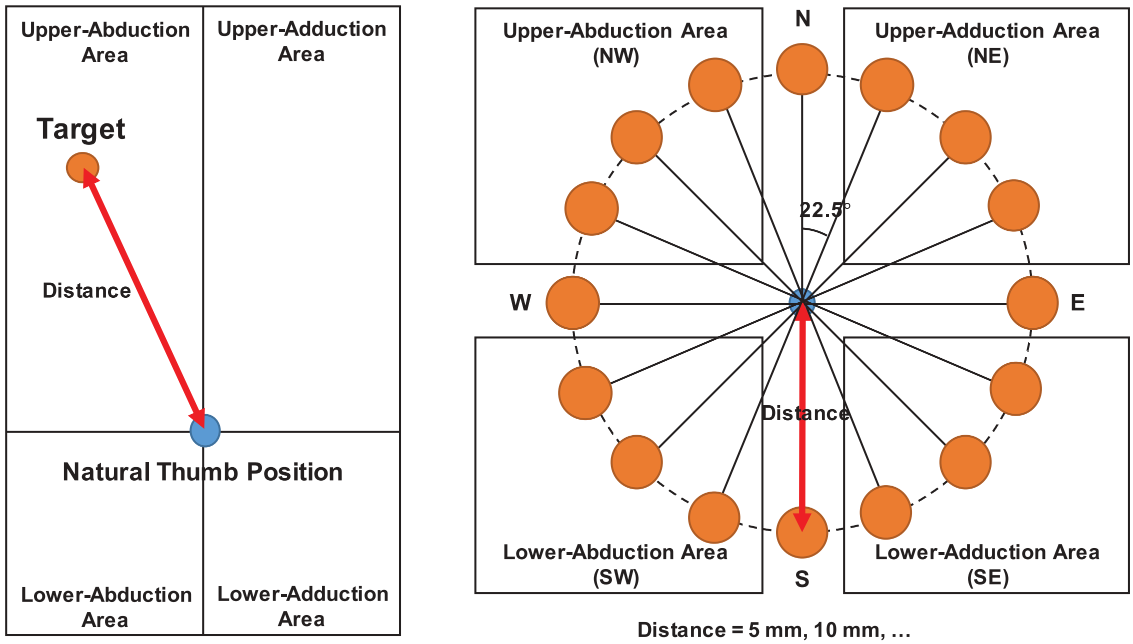

Figure 3. Experimental task paradigm.

In the main experiment, we conducted a user experiment utilizing a tapping task while considering the target distance and target direction. The target distance was varied by the distance from the center of the natural thumb position to the center of the target position. The minimum distance was 5 mm, and the distance was increased in increments of 5 mm. In addition, the target directions were set as shown in Figure 3: the upper-abduction area (NW), upper-adduction area (NE), lower-abduction area (SW), lower-adduction area (SE), and cardinal points (N, E, S, W) (Figure 3). To determine the level of the target direction, the tapping target was positioned at 16 locations with identical target distances. In other words, the interval between the target icons with the same distance from the natural thumb position was 22.5°. Based on the target position, we divided the target direction into each area.

Data for three types of dependent variables were collected to investigate touch behaviors. First, the task performance data were collected, including the success rate and movement time. Each tapping behavior was designated as success, fail, or success after fail. When calculating the success rate, we only included the success trials, while excluding the success after fail trials. The movement time was the period starting when the tapping target appeared and ending at the time that the tapping behavior was performed. We only included the success cases when calculating movement time. The throughput was measured as an additional index of task performance, because throughput was relatively constant and not affected by the task condition, and showed a trade-off effect between the speed and accuracy (Kim & Jo, 2015; MacKenzie, 2015; Roig-Maimó et al., 2017). The throughput was calculated as follows:

$$\text{Throughput} = \frac{Index\ of\ Difficulty\ (ID)}{Movement\ Time\ (MT)} = \frac{\log_2\left(\frac{A}{W}+1\right)}{MT}.$$

In this formula, A represents the movement amplitude and W is the target width. In the present study, target distance was substituted for movement amplitude. The touch accuracy was calculated by measuring the X- and Y-coordinates based on previous studies (Im et al., 2015; Jeong, Kim, Yum, & Hwang, 2016; Park & Han, 2010b).

2.3. Experimental task

To conduct a user experiment to examine the touch area of smartphones, we developed an experimental paradigm using a tapping task based on the following two approaches. First, the tapping task was designed taking into account the actual touch behaviors of smartphone users. When users interact with a smartphone with one hand, they hold the smartphone device using their palm and four fingers and place their thumb comfortably on the screen. Based on this posture, they move their thumb to the target when they want to tap the icon. Considering this posture, we introduced the concept of the natural thumb position on the screen. The natural thumb position means the point of the thumb when users hold the device naturally. We designed the tapping task by considering the natural thumb position to be the central position for the tasks. This approach was similar to the method used by Bergstrom-Lehtovirta, Oulasvirta, and Brewster (2011). Second, we extended the existing Fitts' law paradigm. Previous studies usually followed the ISO standard tasks when they evaluated the pointing behaviors of touch interfaces (ISO 9241-411). This method is an effective way to examine pointing performance when the target distance and size are controlled. However, in the case of ISO tasks, there is a difference compared to the way users perform actual touch behaviors on smartphones. Because we set the natural thumb position to consider the actual touch context during one-handed interaction, the target distance was controlled from the natural thumb pointing position (Figure 3).

The tapping target was presented using a developed experimental application. The touch icon used in the tapping task was a circle-shaped target with two sizes, 5 mm and 10 mm. The basic flow of the task was that participants tapped the target as quickly and correctly as possible. If a participant touched the target correctly, the next target immediately appeared. There were two types of tapping targets in this task, which were alternated. The first type always appeared in the same location, which was at the natural thumb position. The purpose of the first type was to place the thumb at the natural position when the participants performed the touch task. The second type acted as a target for the smartphone users to actually tap the icon. Therefore, the second type appeared across the entire screen area in pre-designated positions considering the target distance and direction. The second type appeared randomly among these pre-defined positions.

2.4. Apparatus

We used actual smartphone devices considering the specifications of premium smartphones to enhance the ecological validity. However, it was doubtful whether using any specific device would affect the results because of any particular form factors or design factors. Thus, we used four smartphone devices with similar screen sizes, device heights, device widths, and device thicknesses. The display size, dimensions, weight, and resolution specifications of these devices are: Sony Xperia XA1 (5.0 in,$145 \times 67 \times 8$mm, 143g, 720×1280pixels), Samsung Galaxy S7 (5.1 in, $142.4 \times 69.6 \times 7.9$mm, 152g, 1440×2560pixels), Sony Xperia XZs (5.2 in, $146 \times 72 \times 8.1$mm, 161g, 1080 $\times$1920pixels), and LG G5 (5.3 in, $149.4 \times 73.9 \times 7.3$mm, 159g, 1440×2560pixels), respectively. Although differences in the form factors were small, they could have affected the touch behavior results in terms of the entire screen area. However, we assumed that there were weak relationships among these form factors and the independent variables of the present study, because we controlled the levels of the independent variables after setting the natural thumb position of each device.

2.5. Participants

Totally, 66 participants (34 males, 32 females) were recruited with an average smartphone experience of 7.30 years (SD = 3.06). Their ages ranged from 19 to 39 years (M = 29.1 years, SD = 4.81). All of the participants preferred using their right hand for smartphone interaction, or they were ambidextrous. The average hand length, palm width, thumb length, and thumb width were as follows: 181.96 mm (SD = 13.81), 84.60 mm (SD = 8.83), 62.58 mm (SD = 5.87), and 20.94 mm (SD = 2.57), respectively. All of the participants had normal vision acuity, and they could move their right arm and hand without any physical difficulties.

2.6. Procedure

The experiment began with an explanation of the research objectives and test procedure. The participants did not know the exact experimental variables; however, they were aware that the experiment was to test the usability of one-handed interaction with smartphones. All of the participants understood the test procedure and agreed to take part in the experiment. After the participants were welcomed, basic information was collected, including their demographics and hand sizes. Before starting the main tasks, the participants had time to practice the tapping task using the training device. The participants began the main experiment after completing all preparations. Participants performed the tasks on each of the devices in the predetermined order of devices using a random number sampling method. If the participants wanted to take a rest, they were given a short break.

2.7. Data collection and analysis

All of the data were automatically collected by the experimental application. Because the purpose for using the natural thumb position target was to place the thumb at the basic position, we excluded the data for this target. We collected the task performance data (success rate, movement time), information throughput, and touch accuracy. The collected data were aggregated by calculating the mean scores of each participant according to target distance and direction regardless of the device.

Statistical analyses of these data were conducted to examine the effects of target distance and direction on touch behaviors. We checked the normality of the data before conducting each statistical analysis. However, the data were not normally distributed because there were multiple levels for the two variables. Therefore, we conducted a non-parametric analysis of variance (ANOVA) after transforming the data using the aligned rank transformation methods (Wobbrock, Findlater, Gergle, & Higgins, 2011). Pairwise comparisons following ANOVA were performed by the Mann–Whitney test with a Bonferroni-corrected post hoc analysis. We analyzed all the data using IBM SPSS 24.0, with a significance level of 0.05.

3. Results

We analyzed the results in relation to target distance and direction. In the case of direction, the quadrant areas containing NE, NW, SE, SW, and the axis direction were analyzed separately.

We analyzed the results in two groups (quadrant areas and axis direction) for the following reasons. First, there are different interaction situations that require axis direction movement and movement in quadrant areas. Second, the natural thumb position was approximately at the bottom of the screen; hence, the target in the upward direction had a longer distance. Therefore, it is possible to analyze touch behaviors according to distance and direction more precisely by dividing the results into two groups.

3.1. Task performances

Success Rate First, we analyzed the effects of the variables on the success rate. In the quadrant direction, the results of the two-way ANOVA showed that there were significant main effects of the target distance [$F(14, 2941) = 15.21$, $p < 0.05$]

and target direction [F (3, 2941) = 5.55, $p < 0.05$]; however, the interaction effects of the target distance and target direction were only marginally significant [F (28, 2941) = 1.38, $p = 0.086$]. In the axial direction, the main effect of the target distance was statistically significant [F (13, 2085) = 9.38, $p < 0.05$]; however, that of the target direction was only marginally significant [F (3, 2085) = 2.17, $p = 0.09$]. The interaction effects between the two variables were significant [F (16, 2085) = 2.69, $p < 0.05$].

Movement Time The movement time was analyzed, followed by the success rate. The analysis results of movement time more clearly revealed the differences in relation to the variables, compared to the success rate. In the quadrant direction, there were significant effects of the target distance [F (14, 2859) = 310.23, $p < 0.05$], target direction [F (3, 2859) = 231.42, $p < 0.05$], and interaction between target distance and target direction [F (28, 2859) = 20.93, $p < 0.05$]. Main and interaction effects of the variables were also found in the axial direction [target distance: F (13, 2009) = 135.77, $p < 0.05$; target direction: F (3, 2009) = 231.42, $p < 0.05$; target distance × target direction: F (16, 2009) = 5.36, $p < 0.05$].

3.2. Information throughput

The information throughput was analyzed in the same manner as task performances. In the quadrant direction, the results showed that the main and interaction effects were significant [target distance: F (14, 2859) = 266.86, $p < 0.05$; target direction: F (3, 2859) = 443.05, $p < 0.05$; target distance × target direction: F (28, 2859) = 17.99, $p < 0.05$]. In the axial direction, there were also significant main and interaction effects [target distance: F (13, 2009) = 275.79, $p < 0.05$; target direction: F (3, 2009) = 457.82, $p < 0.05$; target distance × target direction: F (16, 2009) = 7.77, $p < 0.05$]. After conducting the ANOVA, pairwise comparisons using a non-parametric test with Bonferroni correction were performed to compare the groups. It was difficult to conduct post hoc analyses on all the variables because there were so many combinations within each variable. Therefore, a post hoc analysis was performed only for the throughput data. Figure 6 shows the throughput results for the same group at adjacent distances as arrows, based on the post hoc analysis. The results that were not grouped are not marked.

3.3. Touch accuracy

The touch accuracy was analyzed using the distance of each coordinate from the target to the actual touch point. The distances of the X-coordinate (Δx) and Y-coordinate (Δy) were both calculated. Because we subtracted the target coordinates from the actual tapping target, a positive value meant that the center of the tapping target was located on the right or upper side of the target center. A two-way ANOVA was conducted using the target distance and direction (Table 1). There were significant effects of the target distance and direction on both and Δy in each direction group. Figures 8 and 9 show the average Δx and Δy values according to the target distance and direction, respectively.

4. Discussion

We conducted a user experiment to investigate the smartphone touch area during one-handed interaction based on target distance and direction hypotheses. It was confirmed that the touch performances were significantly affected by target distance and direction. Further, interaction effects between the two variables were also found. These differences could be explained by touch accuracy results using the distance from the target to the actual tapping point.

The success rate and movement time tended to gradually deteriorate as the target distance increased. In the case of the quadrant area, the change tendencies for the success rate were similar in all areas except SW (Figure 4, left). The difference began to appear in the area at a target distance greater than 30 mm. The success rate in the SW direction considerably decreased from 30 to 50 mm. However, it improved somewhat in the other direction. In the area of 50 mm or more, targets were presented only in the NW and NE directions; however, the success rates were found to decrease to similar levels. The change patterns of the success rate were confirmed more clearly by the movement time (Figure 5, left). Although the increased movement time levels were similar within the 30-mm area, the movement time in the SW direction

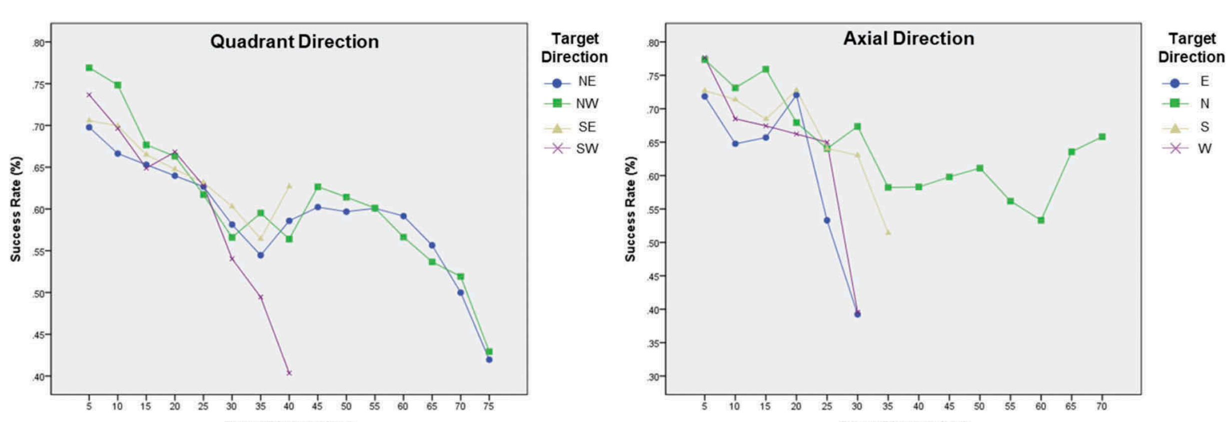

Figure 4. Results of success rate for target distance and direction.

Table 1. Results of two-way ANOVA of touch accuracy.

DV	Factors	df	F	p
Δx (Axial)	Distance	13	3.55	0.000
	Direction	3	48.18	0.000
	Distance × Direction	16	12.03	0.000
Δy (Axial)	Distance	13	13.68	0.000
	Direction	3	104.54	0.000
	Distance × Direction	16	6.65	0.000
Δy(Quadrant)	Distance	14	7.34	0.000
	Direction	3	269.90	0.000
	Distance × Direction	28	19.58	0.000
Δy (Quadrant)	Distance	14	44.95	0.000
	Direction	3	268.91	0.000
	Distance × Direction	28	13.23	0.000

increased sharply for distances greater than 30 mm. When the target distance was 50 mm or more, the movement times for NW and NE were different. Although the error rates for NW and NE were similar regardless of the distance, the movement time for the NW area was much longer than that for the NE area.

In the axial direction, the difference in the success rate was clearly revealed by the movement time. The success rate was highest in the N direction across all of the distances (Figure 4, right). Even the success rate for 35 mm or more in the N direction was higher than that for 30 mm in the other directions. The success rates in the E and W directions drastically decreased in the range of 30–35 mm, compared to the S direction. These differences were clearly confirmed by the movement times (Figure 5 right). Overall, the movement time for the N direction was the lowest across all the distances. The movement time for N at the 50 mm-point was similar to those for S and W at the 35-mm point. Further, the movement time at the 60-mm point in the N direction was similar to that at the 30-mm point in the E direction. The movement time was the longest in the E direction, and the rate of increase was also high up to the 35-mm point. In the S and W directions, the movement times were similar to that of the 25-mm point; however, those for W were higher at the 30- and 35-mm points.

In the case of throughput reflecting the trade-off between the success rate and movement time, an inverted u-shape was found between the target distance and throughput (Figure 6). In the quadrant area, except for the SW direction, the throughput increased within the 40-mm area, and it decreased in the area greater than 40 mm. On the other hand, the peak point of throughput in the SW direction was at the 25-mm point. It was confirmed that the level of throughput increased to the 45-mm point; however, the increase rate in the E direction was lower than those of the other directions. This change pattern for the throughput appeared to reflect the patterns of both the success rate and movement time according to the target distance. The success rate and movement time tended to gradually

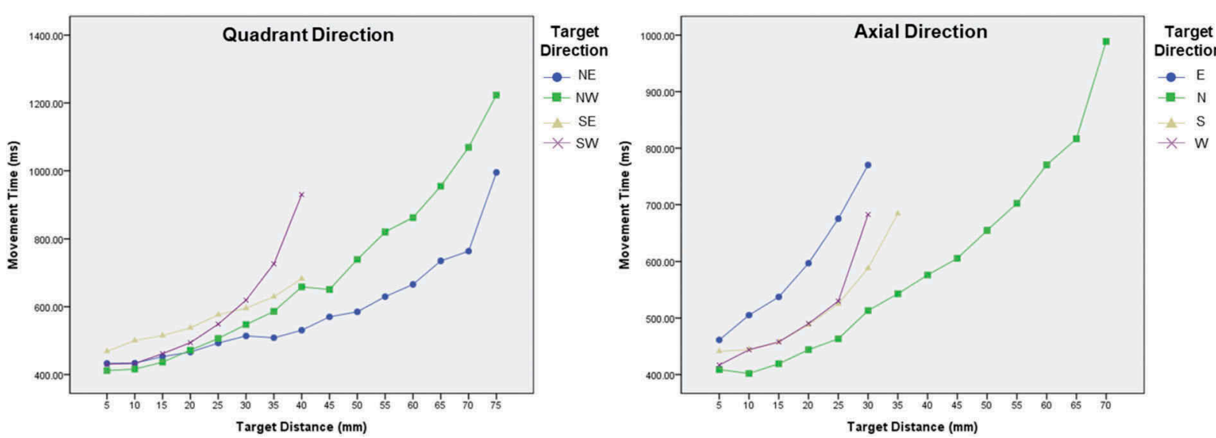

Figure 5. Results of movement time for target distance and direction.

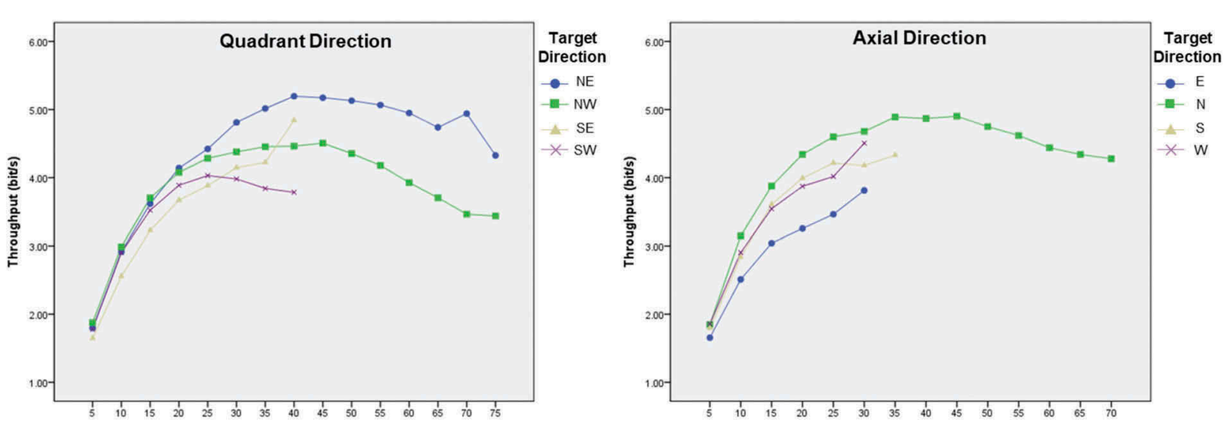

Figure 6. Results of throughput for target distance and direction.

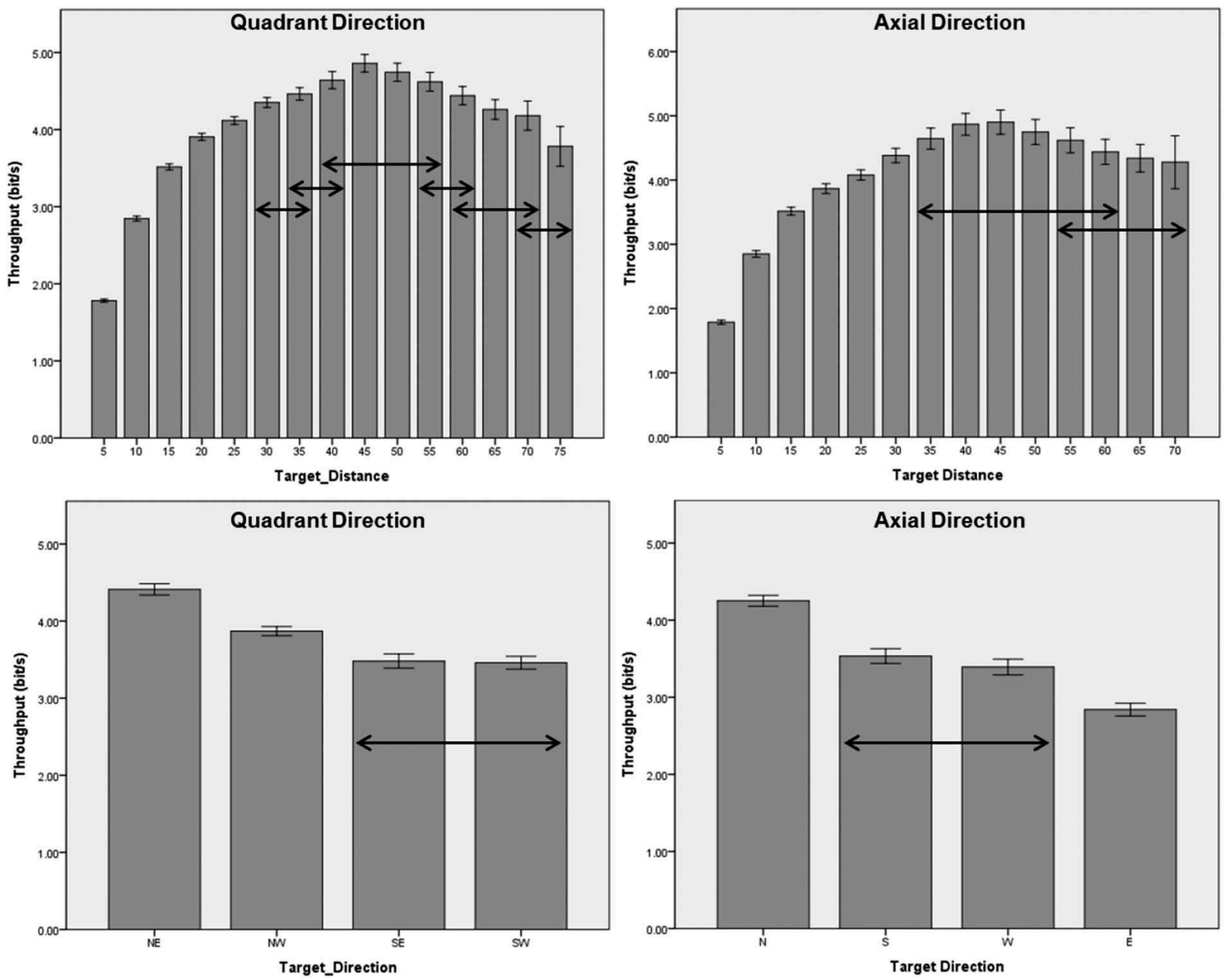

Figure 7. Results of throughput post hoc analysis.

deteriorate as the target distance increased; however, the throughput results were better in the 30–45-mm area. In other words, the results differed somewhat according to the direction, but it could be seen that the touch area where the thumb could move smoothly was within approximately 45 mm from the natural thumb position.

The results for the touch direction did not perfectly fit with the findings of previous studies that supported the conclusion that thumb movement in the diagonal direction was easy (Karlson, 2008; Kim & Jo, 2015; Trudeau, Young, et al., 2012). However, this does not mean that the results of the present study are not consistent with the previous findings. Rather, it indicates that there is a limited distance for comfortable movement. In the case of the upper side, the success rates in the NE and NW directions were similar across the distance range; however, the NE direction showed better movement time and throughput performances compared to the NW direction. On the other hand, in the case of the lower area, the SW direction showed better results than the SE direction at a very short distance within 25 mm; however, the performance in the SW direction drastically deteriorated in the range of 25–40 mm. In other words, the results of the previous studies that the diagonal thumb movement between the upper right area and lower left area was comfortable could be confirmed by comparing the results in the NE direction and NW direction. However, in the case of the SE and SW directions, these results were confirmed only within 25 mm. In other words, the fact that the thumb movement in a diagonal direction was comfortable was also confirmed in the lower area, but the distance limitation was much shorter.

The X- and Y-coordinates of the tapping task were analyzed to investigate touch accuracy. It was confirmed that the patterns of the X- and Y-coordinates of the touch input varied with the target distance and direction. It was interesting that the input patterns were different. In the case of the X-coordinate, Δx had negative values across all directions and distances, except near the proximal area of the hand. In other words, the participants generally touched the left side of the target center. However, the touch point began to appear on the right side of the target center as the touch target moved to the right side from the natural thumb position. This occurred because it was difficult to pull the thumb toward the center of the hand. Therefore, the tendency for the center of the touch point changed, and task performance deteriorated. On the other hand, the results for the Y-coordinate showed a relatively clear tendency. It was found that the touch point was below the center of the target when the target appeared in the upper area (NE, NW, N). In a case where the target was presented in the lower area (SE, SW, S), the touch

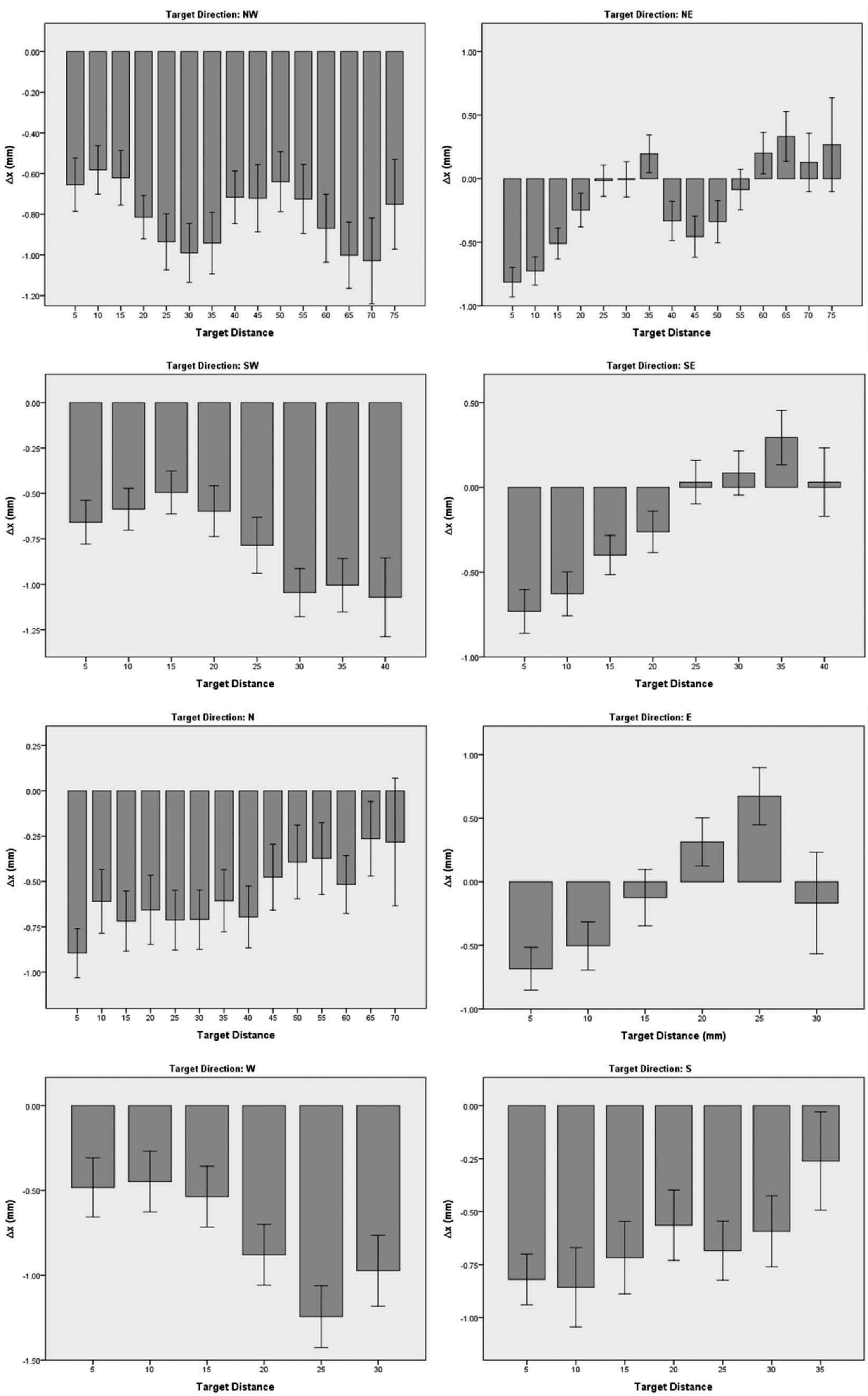

Figure 8. Average distance of X coordinate from target to actual tapping point.

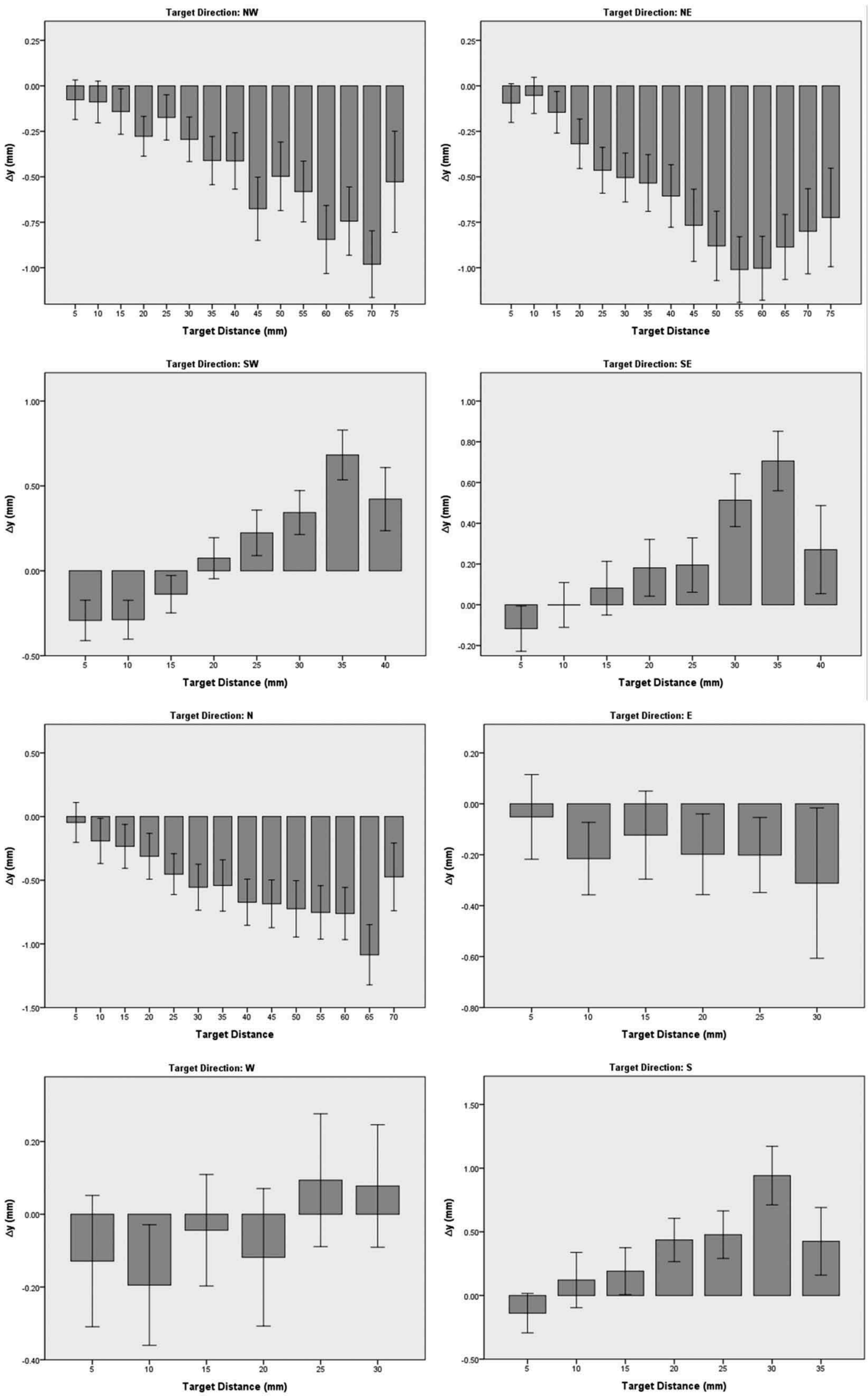

Figure 9. Average distance of Y coordinate from target to actual tapping point.

point was marked below the target when the target distance was very close. However, the touch point gradually moved to the upper side of the target center as the target distance increased. In the case of a lateral movement (E, W), no particular tendency was confirmed.

5. Conclusion

This study examined the effects of target distance and direction on touch behaviors when users performed tapping tasks during one-handed thumb interaction. Although not all of the results were perfectly consistent with our expectations, it was confirmed that most of the findings matched our hypotheses. These findings provide insight for designing a touch interface considering ergonomics and HCI. First, it was confirmed that the proposed experimental task paradigm was useful for evaluating touch behaviors. We could appropriately evaluate touch behavior by setting the natural thumb position and presenting a tapping target from the natural thumb position. This method enabled us to obtain advanced results while confirming the findings of previous studies. Second, the results of the present study will be helpful from both academic and industrial perspectives because they provide insights for a touch interface design based on an understanding of the comfortable touch area.

The present study had some limitations that should be considered in future studies. First, in the main experiment, we used a fixed position of natural thumb position for all participants using the data from the pilot test. Since the natural thumb position is based on the average value of all natural position data, it may be slightly different from the natural position of an individual user. Second, we considered two tapping task variables. However, other external variables, such as device design variables or hand dimensions, may also affect touch behaviors. Further studies should be conducted with these variables. Third, we only used a tapping task when investigating the touch behaviors of one-handed interaction. Recently, various methods such as swiping, pinching, rotating, and flicking are being considered for interacting with a smartphone device. When designing touch interface elements, it would be helpful to also examine these touch behaviors.

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