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Effects of age, thumb length and screen size on thumb movement coverage on smartphone touchscreens

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A B S T R A C T

This study investigated the relationship between the movement coverage on smartphone touchscreens and the factors (age, thumb length and screen size) affecting this. By referring to the thumb movement in the adduction-abduction orientation with a right-hand phone-holding posture, the thumb-coverage area that represents how far the thumb can reach and the centre of gravity in this coverage area were determined. The assessment focused on a comparison of these indices between ages, thumb lengths and screen sizes. The results showed that elderly users and those with longer thumbs are likely to leave more unreachable space at the right side and bottom of touchscreens. Moreover, the thumb-coverage area actually increased when the touchscreen size was increased; however, increasing the size of a smartphone touchscreen does not necessarily increase the thumb-coverage area at the same ratio as the touchscreen size increases.

1. Introduction

With the inclusion of touchscreen technology into mobile phone manufacturing, mobile phones may now be regarded as not only phones but also mobile computers, which facilitate work and help one to live in the Internet world (Bouwman et al., 2014; Choi and Lee, 2012; McCarthy et al., 2013; Othman et al., 2013). Moreover, in terms of mobility, touchscreen mobile phones (generally called smartphones) are supposed to be superior to actual mobile computers (laptops, tablets, etc.), since mobile phones are lighter and smaller, which makes them even more portable (Jewell, 2011; Nortcliffe and Middleton, 2013). In this era of mobile computers, it is believed that touchscreen smartphones will play an increasingly significant role in modern life, and efforts to develop better designs for these devices seem to be intensifying all over the world (Carayannis et al., 2013; Do and Gatica, 2013; Park and Han, 2013).

Apart from pursuing the development of hardware, the improvement of interface designs for touchscreen smartphones is also necessary (Tsai and Ho, 2013). For instance, the layout of PC keyboards is directly transplanted into smartphones, despite the reduced size, in order to fit into palm-size touchscreens. This could potentially cause uncomfortable interactions between the operating fingers and the touchscreen. For example, in order to cover the keys at the corners of the keyboard (single hand operation), the thumb needs to move dramatically across the screen from left to right. The rapid and repetitive movements may fatigue the thumb, which increases typing errors and unnecessary repetitive typing, thereby reducing the use performance.

Moreover, previous studies found that many factors could affect the use performance of small touchscreen devices. According to Xiong and Muraki (2014), the thumb tends to tap faster in an abduction-adduction than in a flexion-extension orientation movement when operating a smartphone touchscreen with a single hand posture. Trudeau et al. (2012) also pointed out that the use of distant keys (compared with the keys close to the lower right corner, right-hand phone-holding posture) on a mobile phone caused the participants to spend longer reaching for them; meanwhile, the precision of pushing those distant keys was also reduced. Besides, it has been found that aging has a degenerative effect on hand functions, especially in terms of precision grip, pinch force and maintaining a steady pinch posture (Carmeli et al., 2003; Ranganathan et al., 2001). In addition, a study found that a small touch button size, poor spacing among the touch buttons and inconvenient location of targets on touchscreen smartphones significantly reduced the finger pointing performance in elderly users (Hwangbo et al., 2013). Muraki et al. (2010) also revealed that

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the elderly tended to have more pushing errors than the young when operating small cell phones with the thumb. However, studies on thumb coverage on touchscreen smartphones specifically for elderly users have rarely been reported. Furthermore, screen size could also be another significant factor that limits the thumb from covering the screen surface; thus, a comparison of the thumb coverage among various screen sizes would be helpful for understanding more about the features of thumb movement on smartphone touchscreens.

This study examined the thumb movement coverage (thumb-coverage area and centre of gravity in the coverage area) by referring to the abduction-adduction orientation on smartphone touchscreens of two different sizes, as well as the relationship between the coverage and user age, thumb length and size of touchscreens. Since the centre of gravity (G) could represent the position of a given irregular rectangular within a defined coordinate system, G was referred to in the comparison of the thumb-coverage position in this study. In addition, this study focused on the keyboard area of the touchscreen, since the upper part of the touchscreen is not likely to be reached by the thumb, especially when the phone is being held with one hand. It is believed that the findings of this study can contribute to a better understanding of the features of thumb movement on smartphone touchscreens, and increase the knowledge base for better designs of user interfaces for not only touchscreen smartphones but also other handheld touchscreen devices with a similar form factor.

2. Methods

2.1. Participants

A total of 48 right-handed individuals who were identified by the Edinburgh Handedness Inventory (Oldfield, 1971) participated in this study and were divided into two groups according to age and thumb length. All participants were mentally and physically able to undertake the experimental tasks, and no visual or auditory problems were reported. None of the participants claimed to have any musculoskeletal disorders or pain, nor any motor symptoms or impaired tactile perception in their thumbs. This study was approved by the Ethics Review Board, Faculty of Design, Kyushu University, Japan, and informed consent was received from each participant.

2.1.1. Age groups

The participants were divided into two age groups, namely, a youth group (12 males and 12 females, mean age±standard deviation [SD] 23.6 ± 1.8 years) and an elderly group (12 males and 12 females, 67.5 ± 3.7 years). The participants in the elderly group claimed to have general knowledge of how to operate a touchscreen smartphone, and they had used tactile keypad mobiles on a daily basis; each young participant owned a touchscreen smartphone for daily use.

2.1.2. Thumb-length groups

The thumb length of the participants was measured and they were accordingly divided into two groups by its median value (97.9 mm), namely, a short-thumb group (4 males and 20 females, 12 young adults and 12 elderly, mean ± SD 93.9 ± 3.5 mm) and a long-thumb group (20 males and 4 females, 12 young adults and 12 elderly, 109.1 ± 5.2 mm).

In this study, the thumb length is defined as the distance between the top of the thumb tip and the apophysis at the proximal end of the metacarpal (Fig. 1). In order to measure the thumb length, the participants were asked to straighten their right forearms and place them comfortably on a desk with the palm facing downwards, with the thumb extended and remaining straight at 45° to the wrist interstate line, along with a comfortable posture and without generating extra muscle effort. The measuring tool used in the experiment was a 200-mm-long sliding caliper with a resolution of 0.1 mm. The age groups showed no significant difference in thumb length using paired T-test (youth group: mean ± SD 102.4 ± 10.2 mm, elderly group: 101.6 ± 8.7 mm). In addition, the longer-thumb group tended to have larger hands than the shorter-thumb group (Table 1).

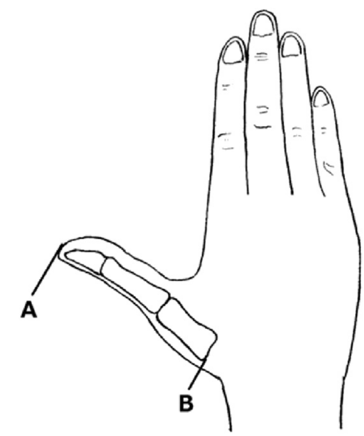


Fig. 1. Thumb length measurement. The distance between A and B represents the thumb length.

2.2. Experimental smartphones

The phones used in this experiment were an actual iPhone4 (phone A) and an actual Galaxy S4 (phone B), since they were considered to be the most popular touchscreen smartphones globally in recent years. The dimensions of phone A were 115.2 × 58.5 × 9.3 mm, with a weight of 140.0 g; and those of phone B were 136.6 × 69.8 × 7.9 mm, with a weight of 130.0 g.

2.3. Protocol

All participants sat comfortably in an armless chair (the height of which was adjustable to match various body heights) in front of a 70-cm-high desk. They placed the tested right arm on the desk in a posture and position that would provide them with acceptable comfort, so that their arms and wrists were fully supported in order to ensure that the participants could concentrate on the tasks during the experiment. The participants were asked to hold the smartphone in a posture matching that which they normally adopt on a daily basis. However, since the elderly participants may not have had sufficient experience using touchscreen smartphones, they were provided with about ten minutes to familiarise themselves with the experimental phones. Then, they decided on the holding posture that would enable them to hold the phones comfortably and steadily.

The experimental task is very simple to undertake since it

Table 1
Comparison of hand length and width between thumb length groups. Values indicate means ± SD (n = 48).

	Short thumb	Long thumb
Hand length (mm)	169.3 ± 9.7	191.6 ± 13.4**
Hand width (mm)	94.7 ± 5.3	108.1 ± 8.5**

T-test: *p < 0.05, **p < 0.01.

requires the participants to perform only an abduction-adduction thumb movement. This movement is easy to learn and not likely to be distorted since it is very distinct from other thumb movements, such as flexion-extension movements. Therefore, it is believed that the lack of experience with a touchscreen smartphone did not significantly alter the thumb posture that was required for undertaking the experimental tasks. In addition, all of the participants were also allowed to shift the holding posture during the experiment to regain comfort, as long as the arm and wrist remained fully supported on the desk. Holding the phone without arm support is likely to result rapidly in discomfort and fatigue in the arm and wrist. Participants may shift their forearms and wrists to regain comfort, so the phone holding posture could be distorted, which could significantly affect the thumb movements and positions on the phone. In order to minimise the effects caused by this shifting action, a forearm support is necessary for the experiment.

2.4. Tasks

The experiment required the participants to undertake a task that involves identification of the four corners of the thumb movement area in an adduction-abduction moving orientation on the experimental phones. The task was divided into two movements, namely, far movement and close movement (Fig. 2). In far movement, the participants moved their thumbs in an ad-abduction orientation as far away as possible from the bottom right corner of the phone, but that would still provide them with acceptable comfort without generating extra muscle effort for the thumb. Meanwhile, they identified the two end points of this movement by tapping the screens of the phones; each end point required 10 taps. In the close movement, the participants were asked to repeat the tapping actions for the far movement; the only difference was that they were asked to move the thumb as close as possible to the lower right corner of the phones with acceptable comfort that did not require extra muscle effort from the thumb.

By connecting the four corners of these two movements, the thumb-coverage area and the position on the smartphone touchscreen could be identified (Fig. 2). The order of these two movements and experimental phones were randomised in the experiment. The participants were required to perform the task as per their usual tapping of the keyboard area. This limited the grip posture as the little finger supports the left-lower corner of the phone, while the right-lower corner of the phone was placed approximately at the base of the thumb. This could reduce the variation of grip posture that may alter the thumb postures and movements.

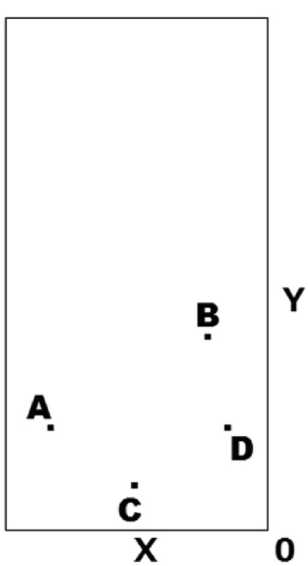


Fig. 2. Four corners of thumb movement coverage on smartphone touchscreens. AB – two ends of far movement. CD – two ends of close movement.

2.5. Prescale technology

In order to identify the four corners of the thumb coverage, the technique used to record the taps of the two movements is important. The tapping recording device used in this study is called Prescale (Fuji Film, Japan). It can measure the pressure distribution of the thumb taps (range of 0.05–0.20 MPa) using the colour-developing sheets that are firmly attached on the screen surface of the experimental phones, namely, micro-encapsulated sheet and colour-forming sheet (Fig. 3).

First of all, a firm overlap of these two sheets is required (the micro-encapsulated sheet is on top and the colour-forming sheet is underneath, with the coated sides facing each other). When applying pressure on the surface, the microcapsules in the micro-encapsulated sheet are broken, which causes the colour-forming material within them to react with the colour-developing material in the colour-forming sheet. This reaction can register the pressure distribution in terms of a red colour in the colour-forming sheet within two minutes.

By scanning the colour-forming sheet with the Prescale Pressure graph Scanner (Model: FPD-9210, Fuji Film, Japan) and analysing and filtering it with the program Prescale Pressure Imaging and Analysis Software (Version 1.0, Fuji Film, Japan), the pressure distribution that represents the thumb movement coverage on the touchscreen can be obtained.

In order to filter the raw data, the Prescale Pressure Imaging and Analysis Software set the deepest degree of the red colour for each sheet as a reference value (100%), and filtered out the area that is 20% lighter than the reference value. This is because the greater repetitive tapping areas represent the areas that participants were more confident with and the microcapsules in this area were more likely to be fully broken to develop a deeper red colour. Thus, the area showing a lighter red colour represents an area that was tapped less. After that, the filtered data were converted into Excel format, so that the thumb coverage could be identified and calculated.

The temperature and humidity of the experiments were well controlled according to the requirements of Prescale's working environment description. In addition, previous studies successfully applied this technology in the measurement of pressure distribution, such as the pressure distribution of the feet in the soles (Aritomi et al., 1983), which shows that this technology could provide acceptable reliability for the present study.

2.6. Measures

2.6.1. The thumb-coverage area on smartphone touchscreens

After the raw data had been converted into Excel format, the pressure distribution of the taps was displayed within a coordinate

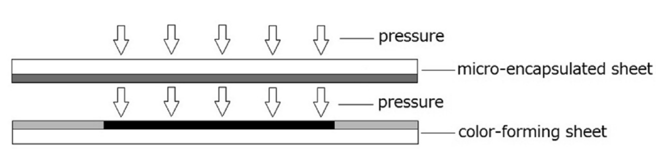


Fig. 3. How prescale measures pressure distribution

axis system, in which the right edge of the screen represents the y axis and the bottom edge represents the x axis (Fig. 2). According to this system, each corner has its own pressure distribution area, so the grids that represent the four corners need to be further defined. For the upper right corner, the column that has a pressure distribution that is closest to the right edge of the touchscreen is selected, and then the grid in this column that is closest to the top edge of the touchscreen is selected. The remaining three corners are also retrieved in this way in order to ensure the thumb coverage that primarily has the greatest value in each sheet. Thus, the entire area and shape of the thumb coverage can be accessed when connecting these four grids of each corner into a quadrangle (Fig. 2).

The position of each corner was calculated by using the same coordinate axis system, and the corner positions and thumb-coverage area were first calculated for each participant; the final values were the mean values across all of the participants, with the variability represented by the standard deviation.

2.6.2. The centre of gravity in the thumb-coverage area on smartphone touchscreens

After the thumb-coverage area had been obtained, the position of this area could also be calculated. This study used the centre of gravity (G) in the thumb-coverage area to represent the position of thumb movement coverage. To determine G of the thumb movement coverage, the following instructions were followed. Firstly, the grids were connected between the upper right and lower left in the area of thumb movement coverage, and then the grids were connected between the upper left and lower right. Thus, four triangles were created, and G for each triangle could be calculated. Secondly, these four Gs of each triangle were connected into a quadrangle, and then the four corners of this quadrangle were connected by two crossover lines; thus, G of the thumb-coverage area was obtained as the intersection point of these two crossover lines (Fig. 4).

The values of the y and x axes were first calculated for each participant, and then the final values used were the means across all participants, with the variability represented by the standard deviation. Thus, combining the positions of each corner in the thumb-coverage area, a clear understanding of the thumb movement coverage could be achieved.

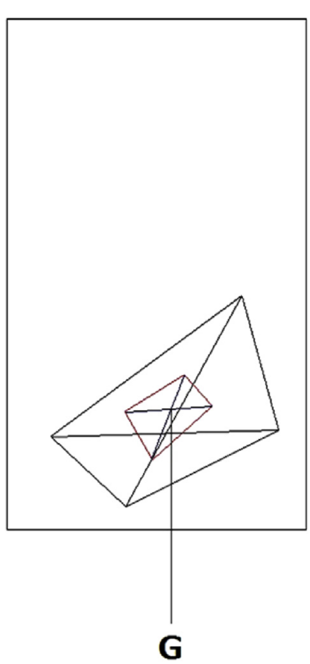


Fig. 4. Coordinate system and centre of gravity (G) in thumb-coverage area.

2.7. Statistics

The results obtained in thumb coverage and G were analysed by two-way repeated measures analysis of variance (ANOVA) to examine the influences of participant-related factors (age and thumb length) and screen size. The differences in hand dimensions between thumb lengths were analysed using unpaired T-test, and the differences in thumb-coverage area and its position between touchscreen sizes were analysed using paired T-test. All tests were conducted using IBM SPSS Statistics Version 20.0.0 (Japanese language package). Statistical significance was accepted at p-values of less than 0.05.

3. Results

3.1. Comparison between young adults and the elderly

In terms of coverage area, no significant main effect of age and interaction of age and screen size, but significant effect of screen size was detected (Table 2). As for G in the coverage area, a significant main effect of age was revealed, but there was no significant effect of screen size and interaction of age and screen size in the X axis; and the elderly group had a greater value in both screen sizes (Table 2, Fig. 5). In the Y axis, significant main effects of the interaction of age and screen size were revealed, but there was no significant effect of age or screen size, and the elderly group had a greater value in phone B (Table 2, Fig. 5).

3.2. Comparison between short- and long-thumb groups

In terms of coverage area, two-way ANOVA analysis revealed significant main effects of thumb length and screen size, but no significant effect of the interaction of thumb length and screen size. Longer thumbs had greater coverage in both screen sizes (Table 3). As for G in the coverage area, in both x and y axes, no significant main effect of thumb length and screen size was revealed, but there was a significant effect of the interaction of thumb length and screen size, and longer thumbs had a greater value in phone B (Table 3, Fig. 6).

3.3. Comparison between the screen sizes

When comparing between screen sizes among all participants regardless of age and thumb length, it was found that the thumb-coverage area for phone B was significantly 1.27 times greater than that for phone A, whereas the screen size of phone B was 1.41 times greater than that of phone A (Table 4).

4. Discussion

4.1. Comparison between young adults and the elderly

In terms of the thumb-coverage area, no significant differences were found in the comparison of the two age groups (Table 2). Generally, the elderly are more likely to have decreased muscle strength and motor functions compared with the young (Plow et al., 2014). This could lead to an assumption that the elderly may have disadvantages in covering a larger area with their thumbs on smartphone touchscreens. However, the thumb length had no significant difference between these two age groups (Table 1). In addition, a previous study found that the thumb length (top of

Table 2
Comparison of thumb-coverage area and G between the age groups. Values indicate means ± SD (n = 48).

	Phone A		Phone B		Two-way ANOVA:
	Youth	Elderly	Youth	Elderly	Coverage area: Age − N.S. Screen size − p<0.01 Age × screen size − N.S.
Coverage area (mm^2)	1123.3 ± 84.2	1121.6 ± 99.2	1423.9 ± 65.3	1407.2 ± 82.2	G in X axis: Age − p<0.01 Screen size − N.S. Age × screen size − P<0.01
G (mm)					
X axis	27.6 ± 3.3	32.4 ± 4.2	31.5 ± 6.4	38.4 ± 5.4	G in Y axis: Age − N.S. Screen size − N.S.
Y axis	24.7 ± 3.4	25.1 ± 2.5	30.6 ± 4.8	34.7 ± 4.3	Age × screen size − P<0.01

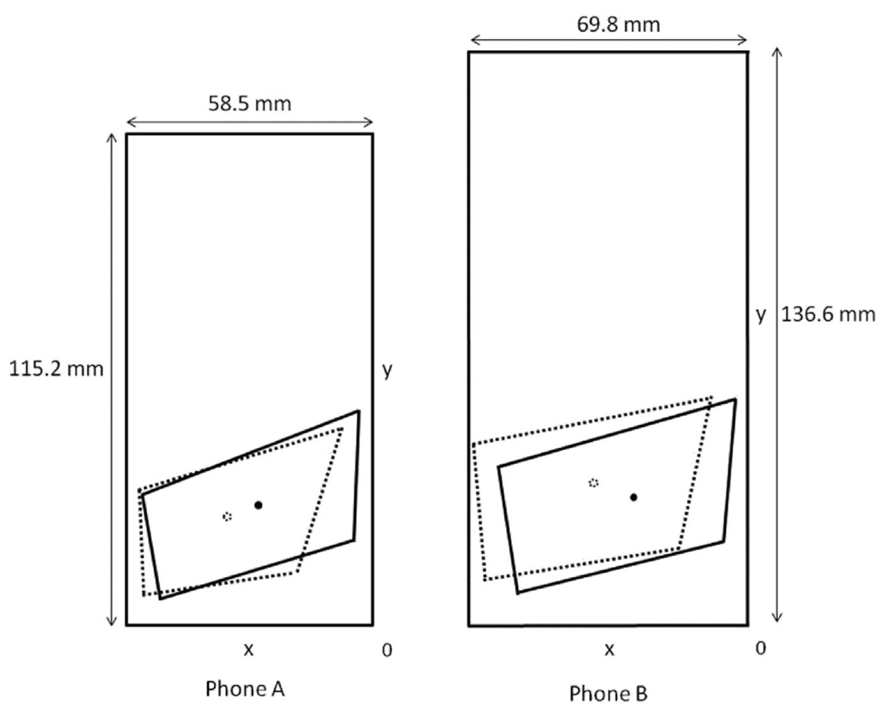


Fig. 5. Comparison of thumb position between the age groups solid line: youth; dashed line: elderly.

Table 3
Comparison of thumb-coverage area and G between thumb length groups. Values indicate means ± SD (n = 48).

	Phone A		Phone B		Two-way ANOVA:
	Youth	Elderly	Youth	Elderly	Coverage area: Thumb length − p<0.01 Screen size − p<0.01 Thumb length × screen size − N.S. G in X axis:
Coverage area (mm^2)	1061.9 ± 64.9	1183.0 ± 71.2	1375.8 ± 72.3	1455.4 ± 51.3	Thumb length − N.S. Screen size − N.S. Thumb length × screen size − P<0.01 G in Y axis:
G (mm)					
X axis	28.3 ± 4.2	31.6 ± 4.7	32.1 ± 4.7	37.4 ± 4.8	Thumb length − N.S. Screen size − N.S.
Y axis	24.5 ± 2.6	26.3 ± 3.1	24.8 ± 3.6	32.7 ± 4.1	Thumb length × screen size − P<0.01

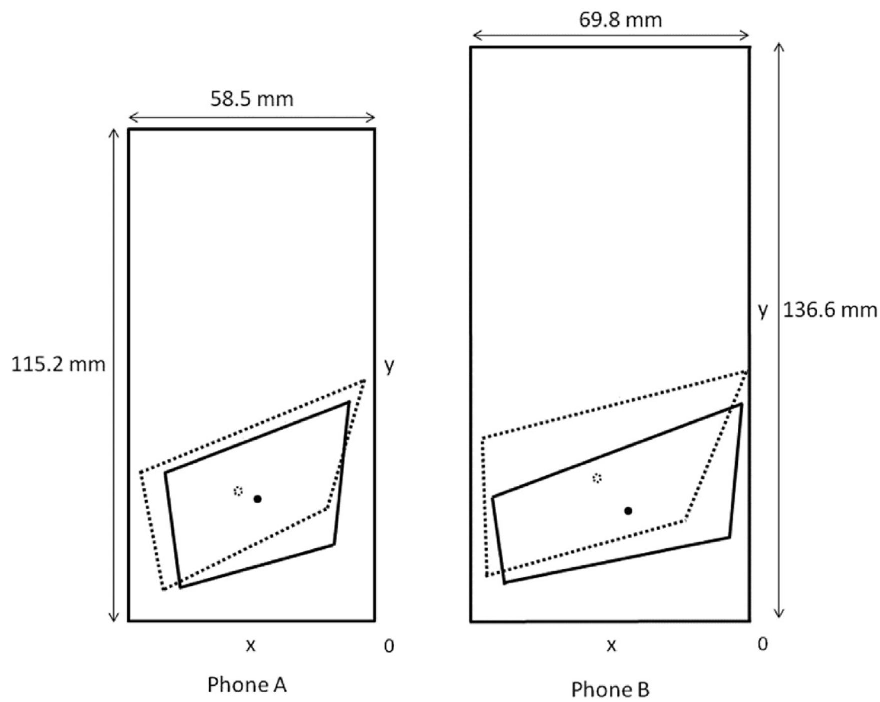


Fig. 6. Comparison of thumb position between thumb length groups solid line: short-thumb group; dashed line: long-thumb group.

thumb tip to proximal end of proximal phalange) had no significant difference among ages from 22.0 to 70.1 years (Muraki et al., 2010). Thus, it is assumed that the finding that thumb-coverage area was not significantly affected by age could have been due to the equivalent thumb lengths in the age groups.

When comparing G in the thumb coverage, it was found that the G for the elderly was significantly further from the right side in both phone A and phone B, and significantly higher from the bottom in phone B (Table 2; Fig. 5). During the experiment, it was observed that the elderly participants were more likely to orientate their thumbs into an oblique posture, whereas those of the young participants were more vertical (Fig. 7 a, b). For elderly participants, lacking experience of using touchscreen smartphones may have contributed to their variation of thumb operating posture; however, since this task is simple to undertake and very distinct, it is considered that the distortion of thumb posture would not have been predominantly due to insufficient use experience, but rather other factors. According to Ranganathan et al. (2001), elderly adults generally have a 30% decreased grip force. Xiong and Muraki (2014) stated that tapping of a smartphone touchscreen while maintaining the stability of the thumb tended to increase the involvement of the first dorsal interosseous (FDI) and the abductor pollicis longus (APL) in order to obtain a greater grip force. Increasing the involvement of FDI and APL could be a challenge for the elderly participants' decreased grip force, which may have caused an uncomfortable feeling due to overexertion of their thumb muscles.

Table 4
Comparison of thumb-coverage area between phones A and B. Values indicate means ± SD (n = 48).

	Phone A	Phone B	Area ratio (Phone B/Phone A)
Thumb-coverage area (mm^2)	1122.5 ± 91.3	1415.6 ± 73.9**	1.27 ± 0.09
Screen area (mm^2)	6739.2	9534.7	1.41

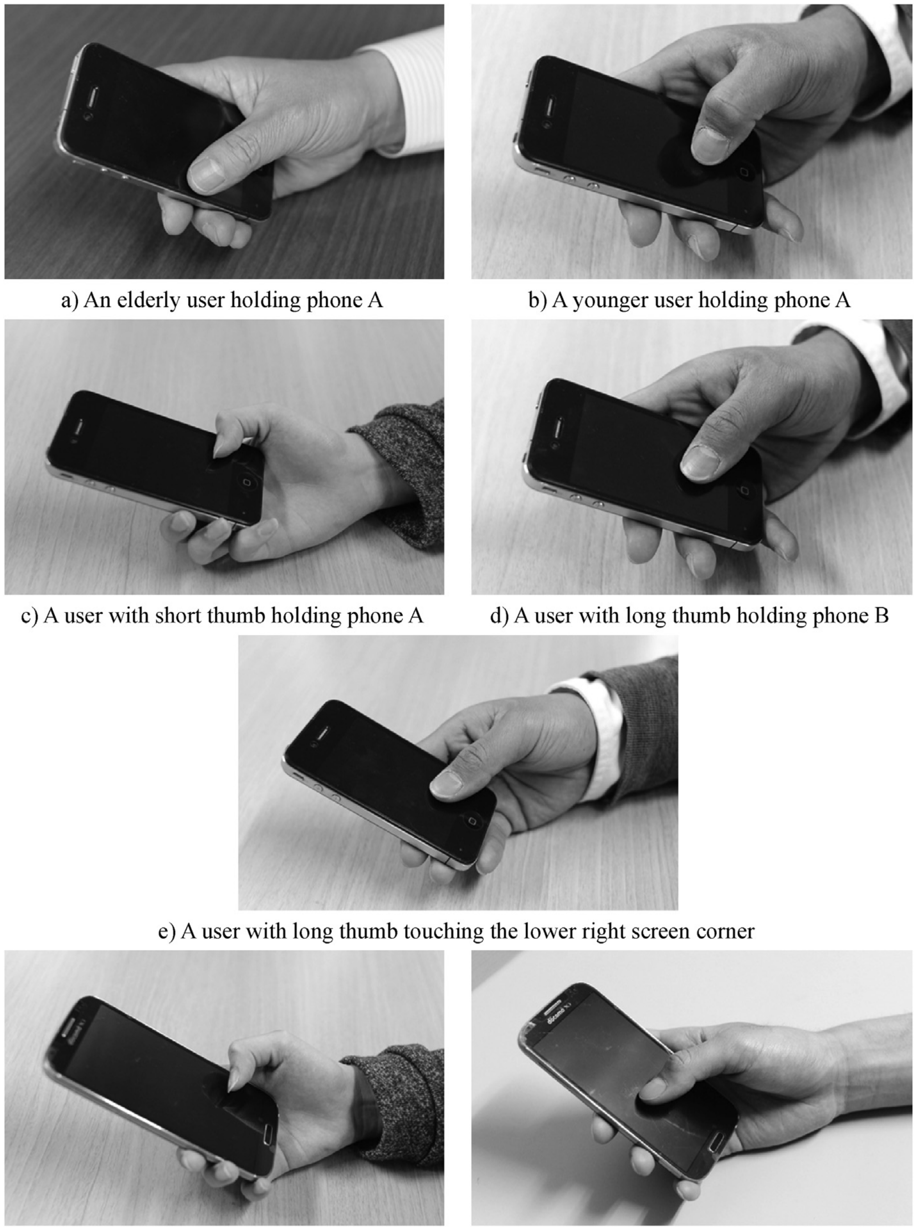
T-test: *$p < 0.05$, **$p < 0.01$.

Thus, in order to regain comfort in the thumbs, the elderly participants may have reduced the involvement of their thumb muscles, including FDI and APL. However, less involvement of those two muscles could lead the thumb posture to become more oblique (Britto and Elliot, 2002; Li et al., 2008; Xiong and Muraki, 2014). Since an oblique posture is likely to place the thumb further away on a smartphone touchscreen (Park and Han, 2010), the elderly participants left more space at the right side and bottom of the screens, which was less reachable.

This shows that age significantly affects G of the thumb-coverage area for both phone A and phone B. Thus, a potential problem in the use of a smartphone touchscreen is that the icons or buttons located on the right side and/or at the bottom of the phone are less likely to be reached by the elderly users (right-hand operating posture). In order to minimise the effects of this problem, the icon/button placement in the smartphone interface should be redesigned. Firstly, icon/button placement at the right side and bottom of the phone should be avoided or minimised. Secondly, the less frequently used icons/buttons instead of the frequently used ones should be placed at the right side and bottom of the phone. Furthermore, the position and shape of the keyboard should be changed for elderly users, especially for large smartphones. It is suggested that the entire keyboard be shifted to the left side of the phone, while the right side of the keyboard should be raised to become a slightly left-slanted keyboard. This would create space without any keys in it at the right side and bottom of the phone. These strategies may cause the thumb of the elderly to be positioned in an oblique rather than a vertical posture, and the uncomfortable feeling in the elderly users would be expected to be reduced.

4.2. Comparisons between long- and short-thumb-length groups

In terms of thumb-coverage area, the short-thumb group had significantly smaller values than the long-thumb group for both phone A and phone B (Table 3). It was observed that the lower right



a) An elderly user holding phone A

b) A younger user holding phone A

c) A user with short thumb holding phone A

d) A user with long thumb holding phone B

e) A user with long thumb touching the lower right screen corner

f) A user with short thumb holding phone B

g) A user with long thumb holding phone B

Fig. 7. Phone-holding postures for the smaller phone (phone A) and larger phone (phone B).

corner of the screen was very likely to be placed at the base of the thumb for those with shorter thumbs compared with those with longer ones (Fig. 7 c, d). Owing to the limited thumb length, those with shorter thumbs had to ensure that the phone was close to the thumb, in order to cooperate with other fingers to retain the phone in the hand. This may have limited the transaction that stabilises the metacarpophalangeal joint, which markedly reduced the extension movement of the thumb (Loebig et al., 1995; Walsh et al., 2011). For those with longer thumbs, the lower right corner of the screen was seen to be away from the base of the thumb (Fig. 7 e). Since those with longer thumbs tend to have larger hands (Table 1), they were able to have greater freedom to hold the phone, which enabled them to place their thumb higher on the screen in order to achieve distant placement, thereby producing a larger thumb-coverage area. However, this does not necessarily mean that those with longer thumbs would always have advantages over those with shorter ones.

In terms of G in the thumb-coverage area, that of the longer-thumb group was significantly further to the right side and higher from the bottom of the screen than that of the short-thumb group for phone B, although no statistically suggestive findings were obtained for phone A (Table 3, Fig. 6). The phone-holding posture is regarded as the key to explaining this difference. It was observed that the participants frequently wrapped their fingers around the width of the phone, which shifted the screen away or towards the thumb. This allowed all participants (both longer- and shorter-thumb groups) to control the space between the screen and the base of the thumb, in order to identify the four corners of the far and close movements. This explains the lack of a difference in G for phone A, since a smaller phone creates less difficulty for the shifting action. However, when the screen size (especially the screen width) was increased from phone A to phone B, this shifting action was greatly limited, especially for those with shorter thumbs. Since those with shorter thumbs also have shorter hand length and width (Table 1), the capability of those with shorter thumbs to wrap their fingers around the width of the phone in order to reach further and higher was limited.

Compared with those with shorter thumbs, those with longer ones had greater control of the space, which led the thumbs to adopt an oblique posture. On this basis, the movements of those with longer thumbs were not likely to be limited at the base of the thumb in the same way as for those with shorter ones, but reaching towards the lower right of the screen would require them to adopt a vertical posture. When the screen size was increased from phone A to phone B, those with longer thumbs had to flex more in order to retain a vertical posture, as the lower right corner of the screen became even closer to the base of the thumb. However, performing thumb flexion movements tends to increase the involvement of the FDI (Brand and Hollister, 1993; Xiong and Muraki, 2014). Since this experiment required the participants to undertake the tasks with a posture that could provide acceptable comfort, the FDI in those with longer thumbs could have been minimised as a consequence.

Therefore, the thumb posture of those with longer thumbs became more oblique rather than vertical, and this oblique thumb posture could have placed the longer thumbs further away from the right side and higher from the bottom of the screen (Park and Han, 2010). These results revealed that, while operating on the keyboard area of smartphone touchscreens (right-hand posture), longer thumbs are likely to reach further and cover larger areas, but leave more space unreachable at the right side and bottom of the screen, especially when the screen size increases. Considering the feature that longer thumbs tend to be positioned in an oblique rather than a vertical posture, it is firstly suggested that, for the design of the input interface on smartphone screens, an option of a removable keyboard position should be provided. This option would be significant for smartphones with larger screens, since users with longer thumbs could adjust the keyboard to a position that leads to a more oblique posture for the thumb. Secondly, for cases in which the keyboard needs to be placed at a fixed position, it is suggested that the right side of the keyboard be raised up to create space at the right-lower corner of the phone. By doing this, the possibility of longer thumbs adopting a vertical posture could be decreased. Through these two strategies, it is believed that the likelihood that the thumb would become susceptible to discomfort could be reduced.

4.3. Comparison of thumb-coverage area between phone A and phone B

In terms of the thumb-coverage area, that of phone B was significantly greater than that of phone A (Table 4). Since phone B is 1.41 times larger than phone A in terms of screen area (Table 4, both width and length of phone B are greater than those of phone A), the participants had to shift their four fingers and thumb around the increased width and length of the phone, in order to retain the phone steadily and comfortably in the hand while undertaking the experimental tasks. This shifting action led to a change of the phone-holding posture, which increased the possibility of the participants' thumbs moving over a larger range of screen size. This suggests that the thumb-coverage area tends to increase with an increasing size of smartphone touchscreens.

However, the increase of the thumb-coverage area does not exactly match the increase of the touchscreen size. As Table 4 shows, the increasing ratio of the thumb coverage was 1.27, which was smaller than that of the screen size by about 10%. According to Furio et al. (2013), the different screen characteristics (weight, thickness, bezel size, etc.) did not influence the participants' evaluation of engagement, satisfaction, ease of use and augmented reality (Azuma, 1997) between an iPhone 3 and a tablet PC (weight difference: 545.0 g, thickness difference: 24.0 mm). Since the differences of weight and thickness between the two experimental phones are 10.0 g and 1.6 mm, respectively, it is believed that these differences would barely influence the phone-holding posture and thumb movements, especially the grip posture and thumb moving orientation as defined in the experimental tasks. Moreover, another study found that screen size (length and width) could significantly affect the texting style (texting with thumb and index finger) on small touchscreen devices (Kietrys et al., 2015). In the present experiment, the participants were required to operate on the keyboard area, which was at the bottom of the phones; thus, the increase of phone length is not likely to create a significant change in the phone-holding posture. Therefore, it is considered that the phone-holding posture was significantly affected by the increase of phone width from phone A to phone B.

The increased screen width led to the change in phone holding posture, which resulted in the limitation of thumb movements. Firstly, in order to hold a wider phone (single right-hand posture), the palm had to open wider, while the fingers had to extend more. This action not only reduced the room between the phone and the hand, but also led to the right-lower corner of the phone being close to the base of the thumb (Fig. 7 f, g). According to Walsh et al. (2011), when the thumb was fixed with tape from the bottom to the interphalangeal joint, it was found that the flexibility of the thumb was greatly decreased, especially in extension movements. This effect is similar to that in this experiment, as the reduced room between the right-lower corner of the phone and the base of the thumb limited the thumb that extends to a more oblique position in order to reach further. Secondly, with the increased touchscreen width, the other four fingers had to wrap and shift more around the phone for undertaking the experimental tasks. In order to maintain the stability of the phone when the shifting action was increased, the palm was limited to a fixed position including the thumb base, which caused the extending capability of the thumb to be reduced.

Owing to the above two factors, the capability of the thumb to extend itself to increase the thumb coverage was limited when the phone size was changed from the smaller Phone A to the larger Phone B. This means that an increase of the touchscreen size does not necessarily increase the area that the thumb can reach and cover by the same ratio. In order to improve the touchscreen interface design for better thumb operation, it is suggested that the thumb operating area should not increase to match a large screen size. For example, in a large smartphone touchscreen, the keyboard layout shall not fully cover the bottom part of the screen, but be slightly smaller to match the thumb coverage. In addition, for a large screen, the placement of keys and icons at the right-lower corner of phone should be minimized (right-hand phone holding posture). These two strategies would reduce the dramatic movements of the thumb, when the flexibility of the thumb is limited on a large smartphone touchscreen. As a result, the uncomfortable feeling in the thumb could be reduced.

4.4. Limitations

Owing to insufficient experience using touchscreen smartphones, the phone holding postures of the elderly may have been somewhat distorted. However, the insufficient experience would not have distorted the thumb operating posture in a way that could have significantly affected the results. The distortion of the phone holding posture may have affected the actual coverage of the thumb used to operate touchscreens. This study limited the grip posture to the bottom part of the phone, which led the thumb to move outward-inward rather than up-down; therefore, all thumb coverage was in the shape of a convex quadrangle, rather than a concave quadrangle. In addition, this study did not involve further discussions of hand length and width that may have affected the phone-holding postures and thumb movements. Furthermore, the weight, bezel size and thickness of the mock-up were not assessed in this study. Compared with the differences in weight, bezel size and thickness between the two experimental phones, the difference in width is much more significant. Thus, this study focused on width as the primary factor among the physical elements of phone dimensions.

5. Conclusions

This study shows that age and thumb length are factors that affect the area and position of thumb movement coverage in an abduction-adduction moving orientation on smartphone touchscreens (right-hand phone-holding posture). It was found that right-handed elderly users and users with long thumbs tend to leave more space unreachable at the right side and bottom of touchscreens. Moreover, increasing the size of a smartphone touchscreen does not necessarily increase the area that the thumb can reach or lead to coverage at the same ratio as the increase in size. The reason for this was that the increasing phone width limits the shifting action of phone-holding posture, which reduces the flexibility of the thumb in terms of extension movement. Taking all of these findings into account, this study suggests that the design of handheld touchscreen interfaces and physical size should include comprehensive consideration of the overall effects of age and thumb length that could significantly affect the thumb coverage on the device.

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