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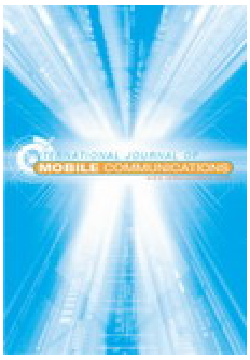

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Effects of aspect ratio and the key position of the smartphone on thumb speed, muscle activities and discomfort in one-handed interaction

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Abstract: This study aimed at investigating the effects of aspect ratio and key location on touch behaviours with one-handed interaction. Two aspect ratio devices (i.e., 16:9 and 18:9) and 15 key locations were examined. Thumb speed, electromyography, and subjective discomfort rating data were collected to examine the touch behaviour. The discomfort rating and electromyography deteriorated with high aspect ratio devices while tapping keys on the lower left of the screen. Higher thumb speeds were associated with adduction-abduction movement such as tapping keys on the lower left and top right. Key tapping with flexion-extension movements such as tapping keys on the lower right and top left tended to have more unsatisfactory subjective ratings and lower thumb speed. These results show that the keyboard design of high aspect ratio smart phones should avoid the common functions and buttons close to the lower left corner.

Keywords: smartphone aspect ratio; touch behaviour performances; one-handed interaction.

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1 Introduction

In the past ten years, the development of computer technology and communication technology had made the smartphone develop rapidly, and the mobile phone had become essential equipment in life and work. With the advantages of portability, mobile phones have gradually replaced desktop computers and notebook computers in many aspects, becoming the main equipment in daily life. In addition, smartphones were widely used for activities such as taking a photo, listening to music, watching a movie, or social networking services, especially college students who spend much time on their phones every day (Berolo et al., 2011). There are many factors that affect the smartphone user experience (Kim et al., 2018), including good availability (Kim et al., 2020), self-efficacy of mobile apps and perceived usefulness (Baker-Eveleth and Stone, 2020). In addition, cultural differences also play an important role in the choice of smart phone (Sanakulov and Karjaluoto, 2017).

At present, enhancing screen to body ratio is an essential direction of mobile phone development. Putting a big screen in a smaller body is an effective solution for a mobile phone that is both large-screen and portable. Smartphones with an aspect ratio (18:9) are gradually becoming the mainstream as Samsung released the flagship Galaxy S8 (Nick, 2017).

Although high aspect ratio smartphones bring us a significant visual impact and a larger browsing window, from the perspective of ergonomics, the increase in aspect ratio may bring some difficulties for users to grasp with one hand. However, people usually operate mobile phones with one hand (Steven, 2013), increasing the device aspect ratio may have a negative impact on grip comfort and it was more difficult for users to tap keys that close to the top and bottom bezel.

Previous studies had demonstrated that performance of thumb was affected by the factors such as key locations, size of the device and the movement directions (Campos et al., 2014; Park and Han, 2010a, 2010b; Trudeau et al., 2012). Using the inertial motion tracking system, the motion angles for each thumb joint relative to its comfort position were calculated. The collected data were used to calculate the discomfort index and the contact area over the total thumb workspace. A smartphone application was optimised by moving the back button from the top left to the middle-upper part (Campos et al., 2014).

Trudeau et al. (2012) reported that it tokens more time for the thumb to reach keys such as lower right and upper left and suggested that the most used functions and keys should be placed away from thumb's limits in flexion or extension. Park and Han, (2010a) revealed that the performance of time-dependent measurement is the best when the touch key size is 7 mm and 10 mm, while the measurement results of error quantity and subjective satisfaction are the best when the touch key size is 10 mm. Furthermore, when doing a one-handed interaction, the touch accuracy decreased as the target distance from the natural thumb position increased (Lee et al., 2019).

In addition, the size of the phone also affected the performance of the thumb in the case of a one-handed grip (Lee et al., 2018; Pereira et al., 2013; Xiong and Muraki, 2016a). In the case of a one-handed grip, Xiong and Muraki (2016a) investigated the thumb movement coverage on smartphone touch screens. They found that the thumb coverage did not increase as the increase of the screen size. Meanwhile, the increasing of screen reduced thumb flexibility by forcing the user to change the grip posture. When the curvature is moderate, the curvature rate of the smartphone has an impact on the hand comfort, and it records less muscle activity than the tablet device (Kwon et al., 2016). Kietrys et al. (2015) found that screen size affected muscle activity. Specifically, larger screen sizes caused higher muscle activity in forearm/wrist flexors and extensors upper trapezius. A few studies have investigated the impact of aspect ratio on the availability of smart phones. Lee et al. (2018) found that success rate and completion time decreased with the decrease of the bottom frame level. In addition, under the condition of smaller bezel, palm touch error is more common. In summary, the results indicated that it became more and more difficult to complete the tasks when the bottom bezel level decrease. Besides, the degree of side curvature in smartphones also affects subjective feelings (Lee et al., 2020).

For high aspect ratio smartphone, it required more considerable effort to reach the keys on the corner of the screen, which could cause thumb pain and damage, especially for the smartphone addiction users (Kim, 2013). Campos et al. (2014) found that tapping keys on the right half of the screen caused great Euler angle of thumb joint, which means the higher uncomfortable value. Besides, excessive use of a smartphone may cause musculoskeletal symptoms (Toh et al., 2020).

The activity of finger muscles, such as force and fatigue, could be described by the EMG signal (Disselhorst-Klug et al., 2009; González-Izal et al., 2012). Chang et al. (2017) evaluated the usability of interaction by muscle activities and discomfort ratings. Finger muscle activity was identified with a standardised EMG signal. The reduction of median frequency (MDF) of the power spectral density was regarded as the fatigue of the muscle (Barszap et al., 2016). This paper mainly studies the muscles related to thumb movement. From the perspective of biomechanics, the movement of thumb is mainly related to abductor pollicis brevis (APB), abductor pollicis longus (APL), and first dorsal interosseous (FDI). Therefore, the EMG signals of these muscles was measured for further analysis.

Whether the high aspect ratio form factor of smartphone caused an effect on thumb performance when operating with a single hand is unclear, so it is meaningful to evaluate the touch performance of high aspect ratio smartphone operation. Especially, EMG signals were measured to reveal effort that thumb muscles needed, thumb moving speed was used to reflect the interaction efficiency and subjective discomfort rating was adopted to investigate issues of comfort. Finally, a comprehensive high aspect ratio smartphone HMI evaluation is formed. At present, mobile phones with high aspect ratio have gradually become a trend, but the (HMI) design has not been deeply optimised. So, it is meaningful to investigate the thumb performance and subjective evaluation during operation with high aspect ratio smart phone.

However, this field has not been deeply studied. Aspect ratio of mobile phone was studied as a variable for the first time in this study. To achieve the research purpose, a tapping task experiment based on one hand interaction was designed. We hypothesised that tapping the keys close to the top and bottom of the screen will cause higher muscle activity and discomfort. At the same time, the thumb moving speed will be lower. Mobile phone application developers could optimise the key layout of their application based on the result of the study.

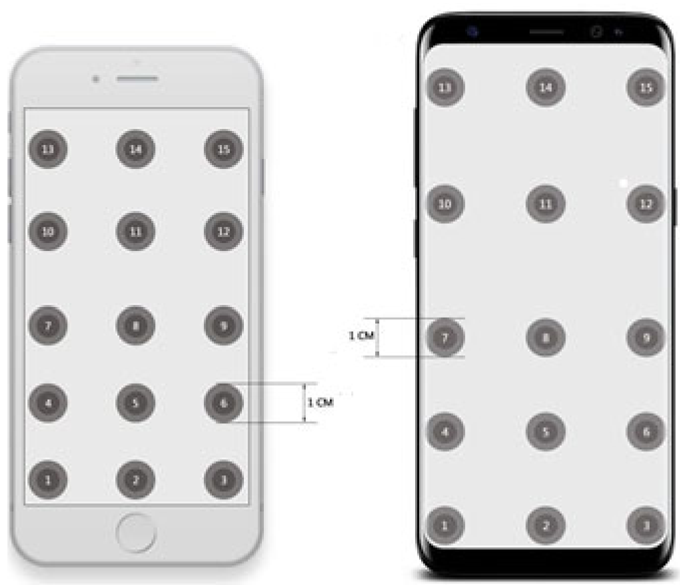
2 Method

2.1 Pre-experiment

Before the main experiment, a preliminary experiment was carried out to investigate which muscle EMG signals should be measured when operating smartphones with one hand and the initial position of the thumb.

Fifteen buttons are distributed on the smartphone screen, as the [Figure 1(a)] shows. The participants were asked to tap the keys in order, from the lower-left corner (key 1) to the upper right corner (key 15). Simultaneously, the EMG signal of muscles related to the thumb movement was measured. Tapping different keys requires different agonists of the thumb. Three muscles, namely the APB, APL, and FDI were tested in the experiment (Lee et al., 2018; Xiong and Muraki, 2016b). In addition, the extensor pollicis longus (EPL) related to the extending of the terminal phalanx of the thumb was also tested.

Figure 1 Position and size of the 15 keys

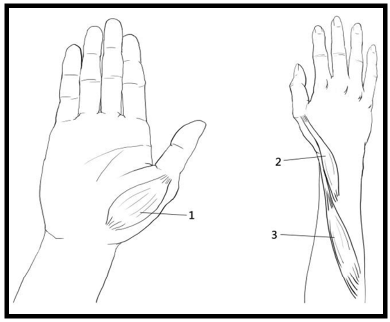


(a) (b)

Eight participants (5 men, 3 women) participated in the pre-experiment. Their age ranged from 21 to 27 years (M = 23.8, SD = 1.83). They were asked to familiarise themselves with the smartphone for a few minutes with one hand posture. Then, the participants were required to finish the pre-experiment. Each key needs to be tapped three times, and the EMG signals were averaged for each agonist muscle.

EMG signal showed that the APB was the agonist muscle of thumb when tapping the keys 1/2/4/5, EPL was the agonist muscle of thumb when tapping the keys 10/11/13/14, and APL was the agonist muscle of thumb when tapping the right column keys 3/6/9/12/15. Combining with the EMG signal and physiological structure of the thumb muscles, the three muscles APB, EPL, and APL were selected for the formal experiment (Figure 2).

Figure 2 The thumb muscles



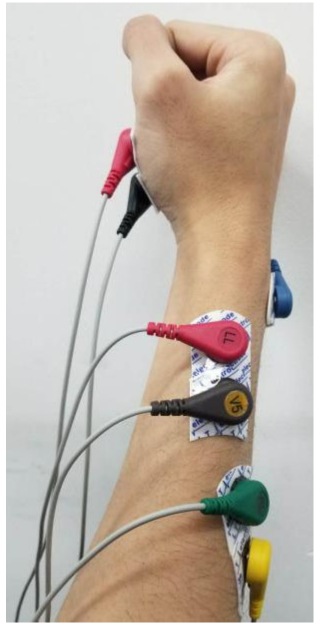
Note: 1 – APB; 2 – EPL; 3 – APL.

2.2 Experimental design

A widely used tapping task was adopted in this experiment (Chang et al., 2017). Two devices Apple iPhone 6® with aspect ratio 16:9 and Samsung Galaxy 8® with aspect ratio 18:9 (Figure 1) was adopted as experimental apparatus. Participants were required to touch all the 15 target keys (diameter: 1 cm) in order with the two devices as quickly and accurately as possible. Each key should be tapped three-time, and after each tapping thumb should be back to the original position. Before the formal experiment, they had listened to the explanation about the details of the experimental tasks. Each key should be tapped, and after each click, the thumb needs to be back to the basic position where the thumb phalange muscles are relaxed. Participants were allowed to familiarise themselves with the two devices for 10 minutes. Next, the experimenter connected electrodes to the target thumb muscles for the participant (Figure 3). After checking the muscle signals, Maximum voluntary contraction (MVC) for each agonist muscle was measured to calculate %MVC (contracting muscle as much as possible). Half of the participants were selected randomly to complete the tapping task with Samsung Galaxy S8 first, and the others used the Apple iPhone 6 first. Then the participants used another mobile phone to complete the tapping task again. After each tapping, participants were allowed to take a short break (about one minute). Each participant should finish tapping tasks with both of the two smartphones, between the two tasks an interval about 30 minutes was provided for relaxing, during the break Borg CR-10 scale (Borg, 1998) were used to measure the thumb discomfort ratings for each key.

Each participant's arrival time was scheduled, and they were required to leave after all the tasks finished. So, the participants had no chance to discuss anything about this experiment with each other. The measurement time were 10 AM–12 AM and 2 AM–5 AM. During these time periods, participants were usually on their best form.

Figure 3 EMG electrodes placed on the forearm and hand (see online version for colours)



2.3 Participants

We recruited fourteen unimpaired right-handed college students (11 men, 3 women) for the study, and the experience in using smart phones must be more than 3 years. The age ranged from 21 to 27 years (M = 23.6, SD = 1.6). The palm length (distance from the bottom of the palm to the tip of the middle finger) ranged from 16cm to 19 cm (M = 17.6, SD = 1.1). The palm span (the distance from the tip of the thumb to the tip of the little finger) ranged from 16 cm to 22 cm (M = 19.6, SD = 1.7).

The participants were asked to familiarise themselves with the smartphone for a few minutes in one hand. Details about the experiments will be told to them before a formal experiment. Participants had no injuries or discomfort to their thumbs and upper limbs, and no vision problems.

2.4 Apparatus

Two smartphones with aspect ratio 16:9 and 18:9 was used to investigate the effect of the aspect ratio. Samsung Galaxy S8 smartphone and Apple iPhone 6 were used for the experiment. The overall size of the Samsung Galaxy S8 was 148.9 mm (height) × 68.1 mm (width) × 8 mm (thickness), and the weight was 155 g. The overall size of the Apple iPhone 6 was 138.1 mm (height) × 67 mm (width) × 6.9 mm (thickness), and the weight was 129g. A rubber veneer was attached on the back of the iPhone6 to ensure that the weight of the two devices is the same. The difference in the width of the two devices was so small that all participants could not feel it. Therefore, the two devices were suitable for research.

The distribution of the 15 keys on the two smartphones was shown in (Figure 1).

2.5 Data collection and analysis

Ethovision xt11.5 software is a commonly used software to study the two-dimensional motion of small animals. We found that Ethovision XT 11.5 can fully measure the two-dimensional motion of the thumb on the screen. A marker that distinguishes the colour from the environment is attached to the thumb nail, and the movement of the marker is regarded as the movement of the thumb.

The electromyography (Bio-Radio EMG unit; Great Lakes NeuroTechnologies, the USA) was used to measure the muscle activity of thumb. The sampling rate of the EMG signal was 1,000 Hz, 10–500 Hz 4 order Butterworth band-pass filter, and notch 50 Hz filter were applied. Root mean square (RMS) were calculated based on the original data. Then, the data were standardised based on the RMS of the maximum voluntary contraction.

To test the influence of aspect ratio and key position, a two-factor (aspect ratio and key position) ANOVA was conducted on the thumb speed, muscle activity, and discomfort rating. The paired t-test was used to compare the thumb speed, muscle activity, and discomfort rating of the 15 keys between the two devices. In addition, a one-factor (key position) ANOVA was conducted for the Galaxy S8 and iPhone 6 on thumb speed, muscle activity, and discomfort rating, respectively. Lastly, the Tukey tests were adopted as post-hoc analysis.

3 Result

3.1 Thumb speed

The results of the two-factor analysis of variance (ANOVA) showed that thumb speeds were only significantly different by key positions [aspect ratio: $F(1, 390) = 0.676$, $p = 0.411$; key position: $F(14, 390) = 12.9$, $p < 0.05$; key position × aspect ratio: $F(14, 390) = 0.612$, $p = 0.856$]. The paired t-test results showed that there was no difference between the two devices in all the 15 keys. However, the speed of the thumb changes significantly on the 15 keys (Table 1). For both two devices, the thumb speed for keys from the lower-left corner to the top-right corner was faster compared to the other keys, and the keys on the lower-right corner and top-left corner were the lowest.

3.2 Muscle activity

3.2.1 Abductor pollicis brevis

The results of two-factor ANOVA showed the significant main effects, but the aspect ratio and key position had no interaction effect on the on APB [aspect ratio: $F(1, 390) = 7.06$, $p < 0.05$; key position: $F(14,390) = 76.74$, $p < 0.05$; key position × aspect ratio: $F(14, 390) = 1.19$, $p = 0.281$]. The paired t-test results showed that the APB activity for keys 1, 4, 7 on Galaxy S8 were significantly greater than iPhone 6 [key 1: $t(13) = 4.71$, $p < 0.05$; key 4: $t(13) = 5.36$, $p < 0.05$; key 7: $t(13) = 2.21$, $p < 0.05$]. The keys 1, 4, 7 were located on the lower left of the original position of the thumb, and the APB is the agonist muscle of thumb when tapping those keys. The two-factor ANOVA and paired t-test revealed aspect ratio had and significant effects on APB activity. For the keys 1, 4, 7, the APB activity significantly increased from a low aspect ratio (iPhone 6) to a high aspect ratio (Galaxy S8). APB activity changed significantly on the 15 keys (Table 1). For two devices, the APB activity for keys on the lower left was greater than the other keys. APB activities for tapping keys close to the original position of thumb were in the lowest group.

Table 1 Average (SD) values for thumb speed (cm/s), muscle activity, and discomfort rating. These values are consistent with the relative positions of the phone keys (Figure 1)

	Galaxy 8			*iPhone 6*		
Thumb speed (unit: cm/s)[b]						
Keys 13, 14, 15	8.9(3)$^{E-F}$	11.9(3)$^{B-F}$	15.5(5)$^{A-C}$	10.0(2)$^{C-D}$	12.2(4)$^{A-D}$	14.7(5)$^{A-C}$
Keys 10, 11, 12	12.7(4)$^{B-E}$	11.5(2)$^{B-F}$	13.2(3)$^{A-F}$	12.6(4)$^{A-D}$	12.3(3)$^{A-D}$	13.3(6)$^{A-D}$
Keys 7, 8, 9	14.9(4)$^{A-D}$	15.6(4)$^{A-C}$	10.5(4)$^{D-F}$	14.9(5)$^{A-B}$	14.4(3)$^{A-C}$	13.2(4)$^{A-D}$
Keys 4, 5, 6	15.9(4)$^{A-B}$	15.5(6)$^{A-C}$	11.1(2)$^{C-F}$	16.2(4)$^{A-B}$	14.0(3)$^{A-C}$	11.7(4)$^{B-D}$
Keys 1, 2, 3	17.8(3)^{A}	12.1(2)$^{B-F}$	7.7(2)^{F}	16.9(4)^{A}	13.3(3)$^{A-D}$	8.5(2)^{D}
%MVC (SE) of APB (%)[c]						
Keys 13, 14, 15	21.3(10)^{C}	10.4(4)$^{D-F}$	9.9(5)$^{D-F}$	18.4(7)$^{B-C}$	9.6(4)$^{E-F}$	9.3(4)$^{E-F}$
Keys 10, 11, 12	17.9(6)$^{C-D}$	8.0(4)^{F}	11.0(6)$^{D-F}$	17.8(6)$^{B-D}$	7.4(5)^{F}	10.7(5)$^{D-F}$
Keys 7, 8, 9	24.3(7)$^{B-C}$	6.0(3)^{F}	9.2(4)$^{E-F}$	21.5(5)$^{B-C}$	5.6(3)^{F}	8.2(4)^{F}
Keys 4, 5, 6	32.0(9)^{B}	7.8(4)^{F}	8.3(4)^{F}	24.8(7)^{B}	6.0(2.8)^{F}	9.4(6)$^{E-F}$
Keys 1, 2, 3	46.2(10)^{A}	16.7(8)$^{C-E}$	8.6(5)$^{E-F}$	39.2(8)^{A}	15.8(9)$^{C-E}$	10.0(7)$^{E-F}$
%MVC (SE) of EPL (%)[c]						
Keys 13, 14, 15	25.1(10)^{A}	12.3(6)$^{B-D}$	11.9(5)$^{B-D}$	20.4(7)^{A}	11.7(5)^{B}	11.4(5)^{B}
Keys 10, 11, 12	17.7(8)^{B}	10.1(5)$^{C-D}$	10.4(5)$^{C-D}$	15.0(4)$^{A-B}$	10.4(5)^{B}	10.4(4)^{B}
Keys 7, 8, 9	15.9(6)$^{B-D}$	9.7(5)^{D}	11.1(6)$^{B-D}$	13.2(5^{B}	8.6(2)^{B}	10.4(3)^{B}
Keys 4, 5, 6	15.7(5)$^{B-D}$	9.7(4)^{D}	10.6(5)$^{B-D}$	13.4(6)^{B}	8.6(2)^{B}	10.7(4)^{B}
Keys 1, 2, 3	17.0(3)$^{B-C}$	10.4(4)$^{C-D}$	12.2(4)$^{B-D}$	15.1(4)$^{A-B}$	13.1(12)^{B}	11.2(4)^{B}
%MVC (SE) of APL (%)[c]						
Keys 13, 14, 15	16.3(9)$^{B-D}$	15.3(7)$^{B-D}$	16.9(8)$^{B-D}$	13.5(5)$^{C-D}$	14.5(6)$^{C-D}$	16.9(8)$^{B-D}$
Keys 10, 11, 12	13.3(6)^{D}	13.1(5)^{D}	19.4(8)$^{A-D}$	13.0(5)$^{C-D}$	12.3(6)^{D}	18.3(7)$^{B-D}$
Keys 7, 8, 9	15.5(8)$^{B-D}$	12.2(8)^{D}	23.7(8)$^{A-C}$	14.0(6)$^{C-D}$	11.5(5)^{D}	21.7(8)$^{A-C}$
Keys 4, 5, 6	14.5(8)$^{C-D}$	12.4(5)^{D}	24.9(8)$^{A-B}$	13.2(7)$^{C-D}$	11.5(6)^{D}	23.6(9)$^{A-B}$
Keys 1, 2, 3	14.0(7)$^{C-D}$	16.2(8)$^{B-D}$	29.1(12)^{A}	12.6(5)^{D}	15.3(6)$^{B-D}$	28.4(11)^{A}

Notes: [a]The superscript letters in the table report the results from the Tukey post-hoc analysis: the same letters denote groups without significant differences. Values with different letters are ranked such that A > B > C. Colour gradients are shown to highlight trends: darker indicates faster thumb speed, greater muscle effortless, and greater discomfort ratings, [b]Higher numbers indicate faster movements, [c]Higher numbers indicate greater muscle effort, [d] Higher numbers indicate greater discomfort.

Table 1 Average (SD) values for thumb speed (cm/s), muscle activity, and discomfort rating. These values are consistent with the relative positions of the phone keys (Figure 1) (continued)

	Galaxy 8			*iPhone 6*		
Discomfort[d]						
Keys 13, 14, 15	5.6(2)^{A}	3.1(1)$^{C–D}$	2.8(1)$^{C–D}$	5.4(2)^{A}	3.4(2)$^{A–B}$	3.4(2)$^{A–B}$
Keys 10, 11, 12	3.6(2)$^{B–C}$	1.6(1)$^{D–F}$	2.1(1)$^{C–F}$	3.2(2)$^{A–C}$	1.9(2)$^{B–D}$	2.6(2)$^{B–D}$
Keys 7, 8, 9	2.6(2)$^{C–D}$	0.6(1)^{F}	2.1(1)$^{C–F}$	2.6(2)$^{B–D}$	1.0(1)^{D}	2.1(1)$^{B–D}$
Keys 4, 5, 6	3.1(2)$^{C–D}$	0.7(1)$^{E–F}$	2.3(1)$^{C–E}$	2.3(1)$^{B–D}$	0.8(1)$^{C–D}$	2.3(1)$^{B–D}$
Keys 1, 2, 3	5.1(1)$^{A–B}$	2.3(1)$^{C–E}$	3.6(1)$^{B–C}$	3.1(1)$^{B–D}$	1.7(1)$^{B–D}$	3.2(1)$^{A–C}$

Notes: [a]The superscript letters in the table report the results from the Tukey post-hoc analysis: the same letters denote groups without significant differences. Values with different letters are ranked such that A > B > C. Colour gradients are shown to highlight trends: darker indicates faster thumb speed, greater muscle effortless, and greater discomfort ratings, [b]Higher numbers indicate faster movements, [c]Higher numbers indicate greater muscle effort, [d] Higher numbers indicate greater discomfort.

3.2.2 Extensor pollicis longus

The results of the two-factor ANOVA showed the significant main effects, but the aspect ratio and key position had no interaction effect on the EPL. [aspect ratio: $F(1, 390) = 4.15$, $p < 0.05$; key position: $F(14, 390) = 12.16$, $p < 0.05$; key position × aspect ratio: $F(14, 390) = 0.66$, $p = 0.811$]. The paired t-test results showed that there was no difference between the two devices in all the 15 keys. EPL activity varied significantly across the 15 keys (Table 1). For two devices, the EPL activity for keys 1, 10, 13 was greater than other keys.

3.2.3 Abductor pollicis longus(APL)

The results of variance (ANOVA) showed that the aspect ratio and interaction effects did not significantly affect the APL. [aspect ratio: $F(1, 390) = 2.733$, $p = 0.099$; key position: $F(14, 390) = 12.04$, $p < 0.05$; key position × aspect ratio: $F(14, 390) = 0.076$, $p = 1.00$]. However, the key position effect was significant. The paired t-test results indicated no difference between the two devices in all the 15 keys. APL activity varied significantly across the 15 keys (Table 1). For two devices, the EPL activity for keys 3, 6, 9 was greater than other keys.

3.2.4 Discomfort rating

The results of the two-factor ANOVA showed the significant main effects, but the aspect ratio and key position had no interaction effect on the discomfort rating [aspect ratio: $F(1, 390) = 6.76$, $p < 0.05$; key position: $F(14, 390) = 17.52$, $p < 0.05$; key position × aspect ratio: $F(14, 390) = 1.12$, $p = 0.339$]. The paired t-test results showed that the discomfort rating for keys 1, 4 on Galaxy S8 were significantly greater than iPhone 6 [key 1: $t(13) = 7.79$, $p < 0.05$; key 4: $t(13) = 3.29$, $p < 0.05$]. Discomfort ratings changed significantly on the 15 keys (Table 1). For Galaxy S8, the discomfort rating for keys 1, 3, 13 were greater than other keys; For iPhone, the discomfort rating for keys 13 was greater than other keys.

4 Discussion

Thumbs increased the agonist muscle efforts to tap the keys around the original position. The agonist muscle of thumb abduction is APB (Chang et al., 2017). The APB muscle activities increased while tapping the keys from the middle left to lower left (from key 7 through 1). The lower the keys located on the left side; the greater muscle activity will cause. The results of the one-factor analysis indicated that tapping key 1 requires more effort from APB. The two-factor analysis results indicated that the factor of aspect ratio has a significant effort on APB activity. This means the keys 1, 4, and 7 on the iPhone 6 is closer to the original position of the thumb. However, the main reasons for this difference were the width of the bottom bezel and aspect ratio. In the experiment, some participants held the two devices in the same posture [Figures 4(a), 4(b)]. The little finger supported the mobile phone from the bottom, and other fingers keep the devices stable. Therefore, the width of the bottom bezel affects the distance between the keys on the lower part of the screen and the original position of the thumb. For Galaxy 8, the bottom bezel is 8mm, and the bottom bezel size of the iPhone 6 is 16 mm. Therefore, the keys on the lower part of the iPhone 6 were closer to the original position compared with Galaxy 8. The results of one-factor (key position) ANOVA indicated that APB activities for key 1 were significantly higher than key 4 and 7. From bezel size, it had a significant effect on APB activity. From the perspective of muscle structure, the APB is relatively short, and the contraction distance is limited. So, tapping key 1 needs more effort, which will cause more discomfort.

However, other participants held a high aspect ratio device in a different posture [Figure 4(c)]. To keep the devices stable, the participants hold the devices with palms closer to the centre of gravity of the high aspect ratio device. Then the keys on the lower part of the screen would be farther away from the original position, and the APB effort to tap these keys would increase. Similarly, the discomfort ratings of keys 1, 4 on the high aspect ratio device are significantly higher. These results were consistent with the previous study for right-thumb in muscle activity and discomfort rating (Chang et al., 2017). However, a previous study showed that no significant differences were found in EMG when operating devices with different bottom bezel (Lee et al., 2018). This inconsistency may be originated from the touch targets layout. Although, different bottom bezel levels mainly affect APB activities when tapping the keys on the lower part of the screen, especially the lower left part. In addition, a discomfort graphical heatmap defined as the sum absolute differences between Euler angles at the comfort and current position in a previous study is inconsistent with our results (Campos et al., 2014). The inconsistency could be originated from the view of biomechanics. The experiment variable of this study (aspect ratio) was also different with this past studies.

Figure 4 Griping postures, (a), (b) griping postures with little finger supported the mobile phone from the bottom. (c) griping postures with palms closer to the centre of gravity of the high aspect ratio device. (d), (e) griping postures while tapping keys on the upper part of the screen (see online version for colours)

(a) (b) (c) (d) (e)

For example, closing the hand into a fist and splaying hands would not cause discomfort, but the Euler angles could be relatively high. The map of APL activity and discomfort rating showed similar propensities.

However, the thumb speeds for keys 1, 4, and 7 were significantly higher than other keys, despite the discomfort rating and muscle activity were relatively high. The map of the thumb speed (Table 1) indicated that speed for keys from lower left to top right was significantly higher than others, and keys 13 and 3 were in the lowest group. These results are consistent with previous studies (Trudeau et al., 2012; Xiong and Muraki, 2016b). Specifically, the tapping speed of flexion-extension orientation task significantly lower than ad–abduction.

The map of the discomfort rating (Table 1) indicated that discomfort rating for the keys on the corners of the screen was greater than keys around the original position of the thumb, especially for the keys 13. Specifically, it was difficult to hold devices stably with the rest of four fingers while the thumb is tapping the key 13 [Figure 4(d)]. This motion could require more activity and an excessive level of flexibility of EPL at the same time (Table 1). However, paired t-test results indicated that there were no significant differences in EPL activity for all the fifteen keys. The hold postures of the two devices were similar while tapping keys on the top half of the screen. To tap keys on the top half of the screen, participants adjusted hold postures to reduce the distance between keys on the top half of the screen and original position of the thumb, then the hold postures of the two devices were similar [Figure 4(d), Figure 4(e)]. The longer part of the high aspect ratio device was outside the palm and did not influence hold posture.

5 Limitation

Although this study has been carefully designed and controlled in a laboratory-based setting, there are some limitations. First, the weight of the two devices was not the same. Second, this experiment does not consider the width and thickness, because the experimental equipment is the actual smart phone. Third, why thumb speed in the flexion-extension orientation lower than adduction=abduction orientation is not clear; a future study should be conducted to examine the fundamental cause of the difference.

6 Conclusions

In summary, this study investigated the effects of aspect ratio and keys position on one-handed interaction. Fifteen keys were placed on two smartphones with different aspect ratios, and muscle activity, thumb speed, and subjective discomfort were measured to analyse the effects of aspect ratio and key positions. The aspect ratio affected APB activity and discomfort rating while tapping keys on the lower-left corner of the screen. Thumb speed for keys form lower left to top right was significantly higher than others. Key pressing at position 3 and 13 tended to have more unsatisfactory subjective ratings and lower thumb speed. This study revealed the activity characteristics of thumb muscles during the operation of mobile phone with different aspect ratio, and the results could facilitate the further study of mobile phone HMI design. The result of the study also helps to improve the user experience of HMI. We expect that the results of the study would be helpful to improve operational efficiency of smartphone software. Furthermore, this method can be used to investigate mobile phones with various aspect ratios and establish a database of click comfort areas. App designers can make targeted optimisation according to the results. Like the idea of establishing driving emotion database and regulation method (Li et al., 2021a, 2021b).

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