Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: https://www.tandfonline.com/loi/terg20

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ERGONOMICS, 2016
VOL. 59, NO. 11, 1462–1472
http://dx.doi.org/10.1080/00140139.2016.1146346

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Grasp and index finger reach zone during one-handed smartphone rear interaction: effects of task type, phone width and hand length

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ABSTRACT

Recently, some smartphones have introduced index finger interaction functions on the rear surface. The current study investigated the effects of task type, phone width, and hand length on grasp, index finger reach zone, discomfort, and muscle activation during such interaction. We considered five interaction tasks (neutral, comfortable, maximum, vertical, and horizontal strokes), two device widths (60 and 90 mm) and three hand lengths. Horizontal (vertical) strokes deviated from the horizontal axis in the range from −10.8° to −13.5° (81.6–88.4°). Maximum strokes appeared to be excessive as these caused 43.8% greater discomfort than did neutral strokes. The 90-mm width also appeared to be excessive as it resulted in 12.3% increased discomfort relative to the 60-mm width. The small-hand group reported 11.9–18.2% higher discomfort ratings, and the percent maximum voluntary exertion of their flexor digitorum superficialis muscle, pertaining to index finger flexion, was also 6.4% higher. These findings should be considered to make smartphone rear interaction more comfortable.

Practitioner Summary: Among neutral, comfortable, maximum, horizontal, and vertical index finger strokes on smartphone rear surfaces, maximum vs. neutral strokes caused 43.8% greater discomfort. Horizontal (vertical) strokes deviated from the horizontal (vertical) axis. Discomfort increased by 12.3% with 90-mm- vs. 60-mm-wide devices. Rear interaction regions of five commercialised smartphones should be lowered 20 to 30 mm for more comfortable rear interaction.

ARTICLE HISTORY
Received 23 October 2015
Accepted 19 January 2016

KEYWORDS
One-handed smartphone interaction; index finger interaction; rear interaction; %MVE

1. Introduction

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

Since smartphones have various usages besides phone calls (web searching, e-mailing, using social network services, note-taking, gaming, and watching videos), large screens are needed. Smartphone screen sizes typically increase in three ways. The first involves rearranging the layout in a limited space while maintaining device width by reducing bezel width, removing or relocating physical buttons (like the home button) on the front to other areas, and/or introducing rear interaction methods. The second approach involves simply increasing the device width (the 'phablet' [phone + tablet] concept). The third approach is a combination of the aforementioned two approaches. Smartphones with foldable displays, which can incorporate a large screen while providing portability, are expected in the near future (Ishii et al. 2012). Indeed, several curved display products, an initial step towards flexible displays, have already been released (e.g. the Samsung Galaxy S6 Edge™, LG G Flex™ series). Smartphones with rear interaction methods (e.g. Pantech Vega™ series, LG G2™ and G3™, Samsung Galaxy S6™) reallocate or duplicate functions of the home and/or side buttons (such as powering on/off, volume controlling, phone answering, screen scrolling, locking/unlocking, selfie taking) on the rear surface of the device. 'Task', 'object geometry' and 'gripper (hand)' can affect grasp (Cutkosky 1989). Smartphone users are likely

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to use different grasps during rear vs. front interaction as front and rear interactions are different tasks, take place at different areas, and require a different digit for touch input (thumb vs. index finger). Therefore, further investigation of the rear interaction method is warranted regarding the effects of interaction tasks, smartphone shape (e.g. device width) and hand size on grasp.

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

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

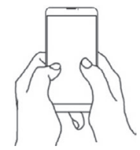
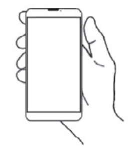
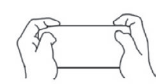
Inconvenient products can cause musculoskeletal disorders (MSDs). Risk factors for MSDs include high task frequency, long task duration, high exertion level, restricted workspace and unnatural posture (Punnett and Wegman 2004). MSDs can occur at the upper extremities, including fingers (tendonitis, tenosynovitis,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

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

2. Materials and methods

Both field and laboratory studies were conducted in the current study. The field study collected data on the grasps used to make vertical strokes on both the front surface of smartphones by the thumb and the rear surface by the index finger. The laboratory study examined index finger rear interaction using vertical strokes and four other strokes (i.e. neutral, comfortable, maximum, and horizontal strokes). Grasps used to make vertical strokes on the rear surface in the laboratory study were compared with those used in the field study. In the laboratory study, the finger reach zone (touch area), subjective discomfort and electromyogram (EMG) of three muscles (first dorsal interosseous

Table 1. Smartphone's primary functions and contexts of use (Expanded from Choi et al. 2013).

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

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

[FDI] muscle, flexor digitorum superficialis [FDS] muscle, and extensor digitorum 2 [ED2] muscle) related to the index finger movements were additionally obtained for each task to analyse the main and interaction effects of rear interaction tasks, device width and hand length on such measures.

2.1. Participants

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

2.2. Design of experiment

The field study collected data on grasps used during front and rear touch interactions on smartphones. Sixty participants scrolled up to view a news article displayed on their smartphones three times using their thumbs. An additional 30 participants scrolled up to view the same news article displayed on an experimental smartphone (Vega LTE-A™, Pantech, Inc.) three times by touching the rear touch area with their index fingers.

The laboratory study considered only rear interactions and used a modified version of Choi et al. (2013)'s analysis protocol for a mobile device. According to this protocol, information was collected on the size and weight of 52 smartphones released in South Korea for the previous three years. The mean size was 144.1 × 73.2 × 8.4 mm (length × width × thickness), the width range was 58.6–85.6 mm and the mean (range) mass was 151.9 g (112–210.5 g). After reviewing the collected information on the major functions and contexts of smartphone use (Table 1), 'sit at desk (with arms on it)', 'operation with the right hand' and 'portrait screen orientation' were selected as the experimental conditions for smartphone rear interaction.

A 5 (task) × 2 (phone width) × 3 (hand length) mixed factorial design was used for the laboratory study. The first independent variable was task type (5 levels, within-subjects factor). It accounted for basic index finger movements during rear interaction: (1) touching the rear area with the index finger in neutral posture (neutral stroke; T_N), (2) comfortably touching the rear area (comfortable stroke; T_C), (3) touching all reachable areas (maximum stroke; T_M), (4) making horizontal lines (horizontal stroke; T_H) and (5) making vertical lines (vertical stroke; T_V). The order of these

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

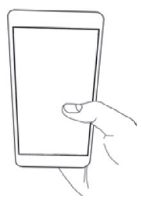
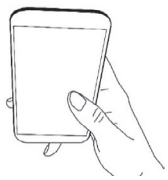
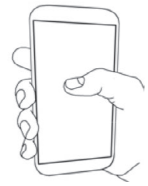
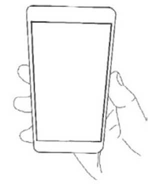
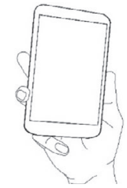
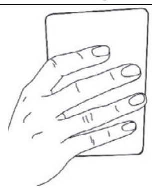
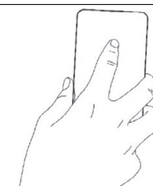
five tasks was determined using a Latin Square. The phone width (within-subjects factor) had two levels: 60 mm (P_N) and 90 mm (P_W) after consideration of the device widths of the 52 smartphones investigated. Based on the hand data of South Koreans aged between 20 and 50 years (SizeKorea 2010), the hand length (a between-subjects factor) was classified into three levels: small (H_S:≤169.9 mm [10th percentile]), medium (H_M: 174.9–177.3 mm [40th–60th percentile]) and large (H_L:≥182.2 mm [90th percentile]). These particular percentile values were selected to ensure a difference of at least 5 mm among the three groups. Stratified sampling was used to obtain an equal sample size per hand group. Dependent variables were the grasps used for rear interaction, the index finger reach zones for each task, the subjective discomfort ratings and EMG readings related to index finger movements.

2.3. Data collection and processing

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

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

Table 2. Classification of smartphone grasps.

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

[ ]Data obtained in laboratory setting.
†Percentage for pooled data ($n = 60$).

In order to analyse the shape and size of the index finger touch area (Figure 1; positive *X*-values are toward the participant's left side), the touch screen area was divided into 2 × 2 mm cells. A cell was regarded as touched if more than 50% of its area was touched during an interaction task. After each task, the participants reported discomfort felt in their right hands on a 100-mm visual analogue scale (VAS: 0: no discomfort at all, 100: unendurable discomfort). In order to determine % maximal voluntary exertion (%MVE) values for abduction, flexion, and extension of the index finger, additional EMG values were measured at maximum voluntary isometric contraction for 10 s. After the first and last 2 s of the collected EMG and MVE data were removed, root mean square values were calculated to obtain %MVE.

2.4. Data analysis

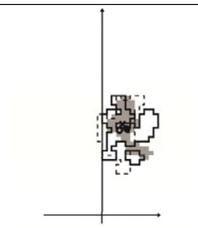
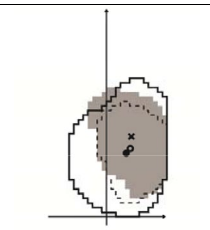
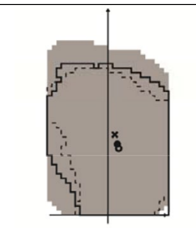
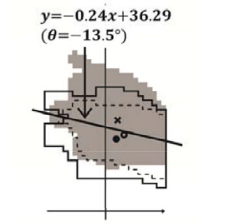
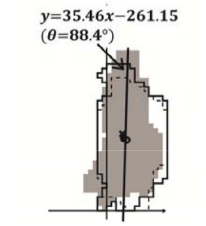
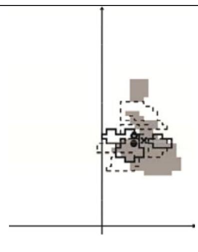
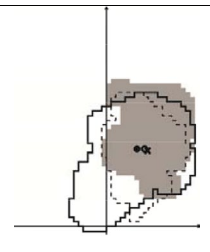
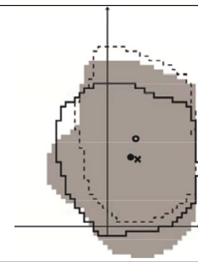
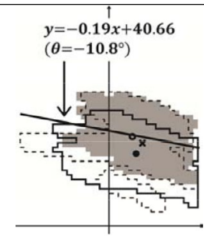
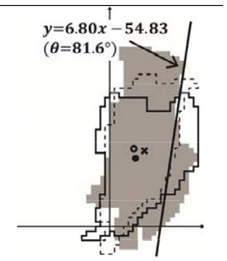
Photographs of smartphone grasps taken during field and laboratory studies were classified by examining each finger's position relative to the phone. The index finger touch areas were compared by task, device width and hand length. The centre point and *X*/*Y* ranges of each touch area were calculated. In the case of T_H and T_V, the slope of touched cells from the *X*-axis (with counter clockwise positions representing positive angles) and the 95% confidence interval (CI) of the slope were calculated using simple linear regression. In addition, a rectangle enclosing the 30 centres of the touch areas (one from each treatment condition) was compared with the rear touch locations adopted by six commercial smartphones. A three-way mixed factor ANOVA was used for both subjective discomfort and %MVE data, with *post hoc* pairwise comparisons done using Tukey's honest significant difference test. Statistical analyses were done using JMP™ (v. 11, SAS Institute Inc., NC, USA), with significance concluded at $p < 0.05$.

3. Results

3.1. Grasp

Grasps examined for both front and rear interactions differed by the little finger's position. Three different grasps were identified for front interactions (Table 2): the little finger on the rear surface (55.0%), the little finger supporting the bottom (36.7%) and the little finger on the lateral side (8.3%). One grasp (holding the lateral sides) was predominantly used for rear interactions (96.7% of cases). All 30 participants in the field study selected this grasp, and only two of 30 participants in the laboratory study used a different grasp (supporting the bottom using the little finger; Table 2).

Table 3. Index finger touch areas for one-handed smartphone rear interaction.

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

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

3.2. Index finger reach zone

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

3.3. Subjective discomfort and muscle activation

The T, P and P × H interaction effects were significant for perceived discomfort (Table 4). T was divided into three groups (T_M, T_HT_V, T_CT_N), with T_M being the most uncomfortable task (58.2 vs. 39.1–14.4; Figure 2). P_W was more uncomfortable than P_N (40.1 vs. 27.8). With regard to muscle activation, four interaction effects (T × P, T × H, P × H, and T × P × H) were significant for FDI, FDS and ED2 (Table 4). For FDI, the effects of T and P were significant. T was divided into two groups ($T_MT_CT_VT_H$ and T_N), with T_N having the lowest muscle activation (5.2–5.4 vs. 4.2). P_N showed greater muscle activation than P_W (5.5 vs. 4.6). For FDS, the effects of T and H were significant. T was divided into three groups (T_C, $T_NT_MT_V$, T_H), with %MVE of T_C being the highest (11.5) and that of T_H being the lowest (6.0). As H-level decreased, %MVE of the FDS increased (from 5.8–7.8 to 12.2). For ED2, the effects of T and H were significant. T was divided into three groups (T_H, $T_VT_NT_C$, T_M), with %MVE of T_H being the highest (8.1 vs. 7.1–5.3). H was divided into two groups (H_S, H_MH_L), with %MVE of H_S being the highest (8.1 vs. 6.3–5.0).

Table 4. Effects of task (T), phone width (P) and hand length (H) on perceived discomfort and %MVE for FDI, FDS, and ED2, which are associated with abduction, flexion, and extension of the index finger.

	p-values			
		%MVE		
Effects	Perceived discomfort	FDI	FDS	ED2
T	<u><.0001</u>	<u>0.013</u>	<u><.0001</u>	<u><.0001</u>
P	<u><.0001</u>	<u>0.002</u>	0.14	0.36
H	0.17	0.45	<u><.0001</u>	<u>0.020</u>
T × P	0.55	<u><.0001</u>	<u><.0001</u>	<u><.0001</u>
T × H	0.28	<u><.0001</u>	<u><.0001</u>	<u><.0001</u>
P × H	<u>0.03</u>	<u><.0001</u>	<u><.0001</u>	<u><.0001</u>
T × P × H	0.38	<u><.0001</u>	<u><.0001</u>	<u><.0001</u>

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

4. Discussion

4.1. Grasp posture

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

4.2. Index finger reach zone

The range of the index finger reach zone (touch area) varied by task. It was affected by device size, the device's centre of mass (COM), hand size, hand length and finger position on the device. During T_H, finger strokes were not parallel to the device's *X*-axis (i.e. slopes were made in the range from −10.8° to −13.5°). During T_V, finger strokes also showed a slope of −1.6° to −8.4° with reference to the *Y*-axis. Such results could have been partly due to the restricted grasp required for rear interaction, as mentioned in section 4.1. When determining the width and height of the rear interaction area for new smartphones, stroke behaviours observed in the current study should be taken into account.

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

The size of the touch area by the index finger during each task varied by H-level as well. During T_C, the reach

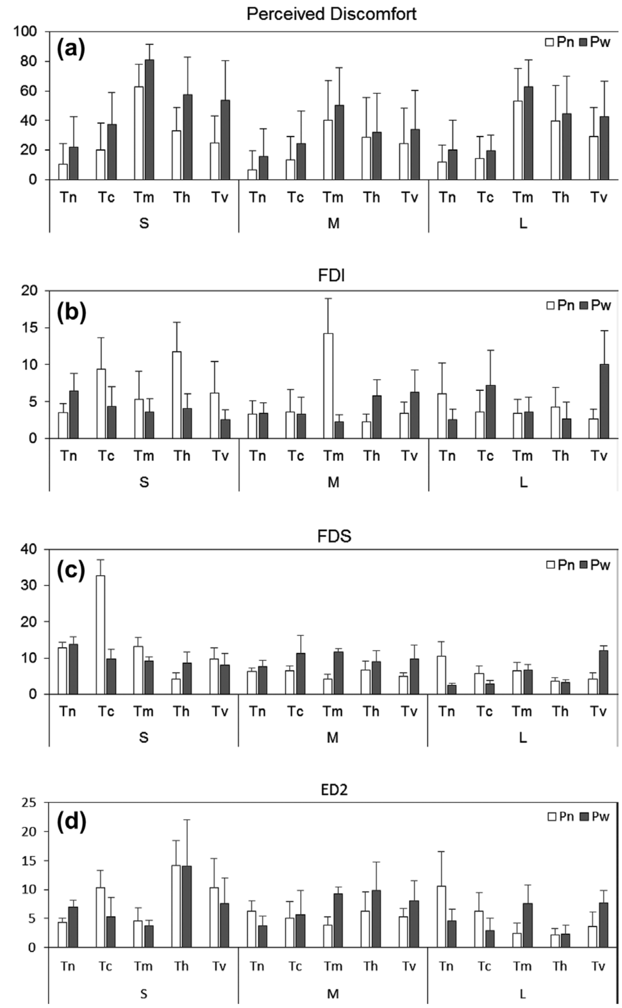


Figure 2. Mean (SD) perceived discomfort (PD) and muscle activation for each H and P level during five different tasks. (a) Perceived discomfort, (b) FDI = first dorsal interosseous muscle; the muscle between the thumb and the index finger, which contributes to abduction of the index finger, (c) FDS = flexor digitorum superficialis muscle; the muscle near the wrist, which contributes to flexion of the index finger, and (d) ED2 = extensor digitorum 2 muscle, the muscle positioned in the middle of the lower arm, which contributes to extension of the index finger.
Notes: Pn – phone width of 60 mm, Pw – phone width of 90 mm, T_N – neutral, T_C – comfortable, T_M – maximal, T_H – horizontal, and T_V – vertical.

envelope was the widest at H_S, probably because the device holding positions could be more diversified by small hands. In contrast, during T_M, the reach envelope was the widest at H_L, mostly due to longer index fingers at higher H-levels.

Rear interaction areas of five commercial smartphones were compared with the index finger touch locations suggested by the current study (Figure 3). The former were 9.8–12.7 cm from the bottom of the device and ± 1.4 cm from the vertical centre line of the device. In contrast, all index finger touch centres observed in the current study

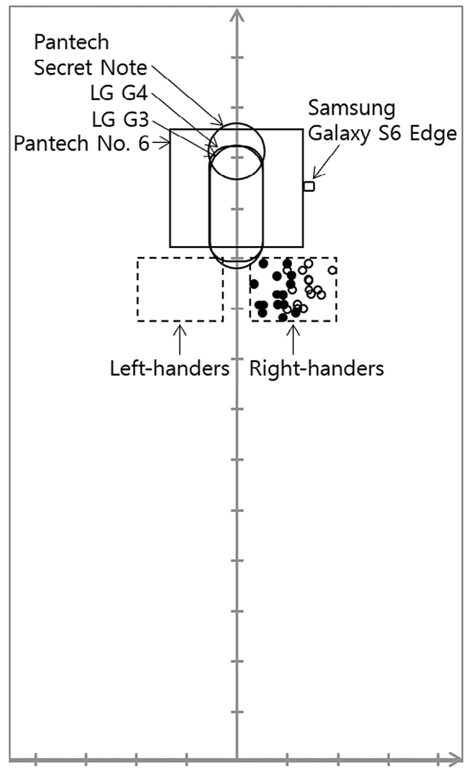


Figure 3. Comparison of the rear touch areas of commercial smartphones and the centres of touch areas for five tasks, two phone widths, and three hand length groups during index finger-rear interaction (Filled circles represent the 60-mm-wide phone, and unfilled circles represent the 90-mm-wide phone; scale marker interval = 1 cm).

were located 8.8–10.1 cm from the bottom and 0.3–2.0 cm to the right of the vertical centre line (0.3–2.0 cm left for left-handed individuals). It is thus expected that rear touch interactions on commercial products could be made more comfortably if their interaction areas were closer to the suggested area.

4.3. Subjective discomfort

Subjective discomfort varied by task (Table 4), mostly due to differences in the direction and range of index finger movements required for each task. Among these tasks, T_M was the most uncomfortable (58.2 vs. 39.1). Participants also reported higher discomfort ratings after using P_W than after using P_N (40.1 vs. 27.8), which is likely due to the decreased degree of freedom of grasp with increased device width. The P × H interaction effect was also significant. After using P_W, the H_S group reported higher discomfort ratings than did the other two groups (50.24 vs. 38.85) and also reported discomfort ratings in the range from 10.2 (T_N) to 62.8 (T_M) for P_N vs. from 22.1(T_N) to 81.0 (T_M) for P_W. If rear interaction is made on a 90-mm wide smartphone, the expected level of discomfort for the small-hand group (hand size < 169.9 mm) is 50.2, while that for the other groups will be in the range from 31.2 to 38.9.

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

4.4. Electromyogram

For %MVE of FDI, involved in index finger abduction, the T effect was significant. %MVE of FDI was the highest during T_C. For %MVE of FDI, the P effect was also significant. Smartphone width affected FDI muscle activation, although the difference was small ($P_N = 5.5\%$, $P_W = 4.6\%$). The *post hoc* analysis of the T × P × H interaction effect showed that the highest (14.2) %MVE for FDI was in the $T_M P_N H_M$ condition, the second highest (11.7) was in the $T_C P_N H_S$ condition and the lowest (4.1) was in the $T_H P_W H_S$ condition. As noted in section 4.2, when small-handed individuals make horizontal strokes on a narrower device, more abductions of the index finger occurred, whereas more flexions occurred for a wider device. Indeed, %MVE for FDS, which involves index finger flexion, increased from 4.3 for $T_H P_N H_S$ to 8.6 for $T_H P_W H_S$.

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

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

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

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

4.5. Limitations

There are some limitations in the current study. First, as only Korean individuals in their 20s participated, characteristics of other ethnic and age groups are unknown. For ethnic groups with larger hands, the maximum reach zones will increase, and for those with shorter hands, the size of index finger reach zones will likely reduce and touch centres likely become lower. For example, the mean (SD) hand length of Americans is 18.7 (1.03) cm (Chengalur, Rodgers, and Bernard 2004) vs. 17.6 (1.99) cm for Koreans (SizeKorea 2010). Age-related differences are also expected. In the case of Korean teenagers, the mean (SD) hand length is 16.9 (1.57) cm; thus, index finger reach zones of this group are expected to be narrower and located in a lower region than were those observed in the current study. Joint ROMs reduce with age (Stubbs, Fernandez, and Glenn 1993). Therefore, index finger reach zones of the older population are likely similar to those of teenagers. For the universal design of smartphone rear interaction, such differences should be taken into account. Second, various hand sizes may have not been reflected in the results of the field study, as it used a random approaching method, and hand size was not evaluated. Third, the ratios of men to women in three hand groups were not well balanced (no, one, and all women for the large, medium, and small hand groups, respectively). As hand function strengths are relatively low for women (23 ± 7 kg vs. 40 ± 9 kg in grasp strength [Chao 1989]), female participants may have felt more uncomfortable with the same device and task than the male participants did. Fourth, changes in the device weight and COM due to the smartphone housings could have affected experimental results. Though the housings were developed to control the size and weight of the two experimental smartphones, the height and weight of the experimental phones were changed compared to the original phones. COMs of the experimental devices were also different from the original COMs, as epoxy is a very light material. These changes could have affected grasp and EMG results, though not substantially. Fifth, reach zones can change with finger input methods. Different touch pressure and finger movements are required for using touch screens and physical buttons, potentially resulting in slightly different finger postures and grasps. Sixth, grasp and grasp comfort can be affected by the sharpness of lateral and bottom edges. The housings used in the current study were rounded with a 1-mm radius for the lateral edges and a 10-mm radius for the bottom corner edges, while actual edge designs vary by smartphone. Seventh, some finger touches were made outside of the touch screen (in the case of T_M and T_H, parts of the left, right, or bottom touch areas were partially truncated). Eighth, the current study considered the 'sitting without desk' condition (30 people in the field study) and the 'sitting at desk' condition (30 people in the laboratory study), but did not consider other conditions (such as walking). Ninth, in the field study, the grasps during rear interaction were observed when scrolling up the screen three times (similar to T_V), but grasps during other tasks were not considered. Tenth, although index finger flexion, extension, adduction and abduction were analysed from the perspective of MSD risk, index finger joint angles, wrist movements (flexion, extension, and ulnar/radial deviation), prolonged task and high task repetition were not considered.

5. Conclusions

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

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Research Fund of the UNIST (Ulsan National Institute of Science and Technology) [grant number 1.090013.01].

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