Determining Ergonomic Smartphone Forms With High Grip Comfort and Attractive Design

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Objective: The authors aimed to identify ergonomic smartphone forms by investigating the effects of hand length, four major smartphone dimensions (height, width, thickness, and edge roundness), and smartphone mass on grip comfort and design attractiveness.

Background: Despite their potential effect on grip comfort and design attractiveness, the dimensions specified above have never been simultaneously considered in a study investigating smartphone gripping.

Method: Seventy-two young individuals participated in a three-stage study. Stage 1 determined the ranges of the four smartphone dimensions suitable for grip comfort and identified the strengths of their influences. Stage 2 investigated the effects of width and thickness (determined to have the greatest influence) on grip comfort and design attractiveness. Mock-ups of varying masses were fabricated using the dimensions determined during the first two stages to investigate the effect of mass on grip comfort and design attractiveness in Stage 3.

Results: Phone width was found to significantly influence grip comfort and design attractiveness, and the dimensions of 140 × 65 (or 70) × 8 × 2.5 mm (height × width × thickness × edge roundness) provided high grip comfort and design attractiveness. The selected dimensions were fit with a mass of 122 g, with masses in the range of 106–137 g being comparable.

Conclusion: The findings of this study contribute to ergonomic smartphone design developments by specifying dimensions and mass that provide high grip comfort and design attractiveness.

Application: The dimensions and mass determined in this study should be considered for improving smartphone design grip comfort and attractiveness.

Keywords: smartphone grip, handheld device, size-weight illusion, smartphone size

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INTRODUCTION

The size of a smartphone design affects both its grip comfort and attractiveness. Increasing smartphone and display sizes can degrade the grip comfort and portability of the device (Chowdhury & Kanetkar, 2017): Models with 3–4" (76–102 mm) screens allow one-hand interaction, whereas widescreen phablet (phone + tablet) phones sometimes require two hands for use. Operating large-screen mobile phones with one hand increases the risk of dropping the device because of grip insecurity (Chiang, Wen, Chen, & Hou, 2013). Additionally, the physical form or design of a product can induce positive aesthetic impressions of design attractiveness, elegance, and beauty (Crilly, Moultrie, & Clarkson, 2004) and influence purchase decisions (Chrisprastika, 2015). As such, both grip comfort and design attractiveness should be considered when determining smartphone sizes.

No existing grip studies have cohesively investigated the four major dimensions (height, width, thickness, and edge roundness) of a rectangular parallelepiped. Some previous studies researched cylindrical objects whose major dimension was their diameter (e.g., Grant, Habes, & Steward, 1992; Kong & Lowe, 2005; Lee & Zhang, 2005; Seo & Armstrong, 2008), whereas others manipulated only one dimension of an object, such as width, and controlled the others, such as thickness and height (e.g., Blackwell, Kornatz, & Heath, 1999; España-Romero et al., 2008; Lee, Kong, Lowe, & Song, 2009; Lee, Kyung, Lee, Moon, & Park, 2016; Ruiz-Ruiz, Mesa, Gutiérrez, & Castillo, 2002; Shivers, Mirka, & Kaber, 2002). Chowdhury and Kanetkar (2017) used seven smartphone models and concluded that 138H × 70W × 8T was the most preferred size considering smartphone width and volume. These two dimensions were, however, not manipulated, and smartphone weight was not controlled, which could have confounded their result. In the case of a rectangular parallelepiped such as a smartphone whose overall form is determined by height, width, thickness, and edge roundness, more than one dimension can affect the gripping posture, and interactive effects may exist between dimensions. Dimensions should thus be considered in conjunction to thoroughly evaluate smartphone grip comfort.

Even for objects of the same shape, grip comfort varies with size. This relationship can be partially explained by the fact that the tactile sensitivity of the hand (in terms such as pressure and vibration) changes across its skin. The distal part of the hand is more sensitive to pressure and vibrations because the density of mechanoreceptive units decreases from the fingertip to the remaining finger to the palm (Vallbo & Johansson, 1984). A two-point discrimination study performed by Vallbo and Johansson (1984) found the mean two-point threshold at the tip of the index finger was 1.6 mm, five times less than the value determined for the palm, indicating the palm is less sensitive. Louis et al. (1984) found the mean value for stationary two-point discrimination in the little finger was 3.3 mm, significantly larger than the value for the index finger (although no exact value was reported for this). As these findings suggest, the just-noticeable difference varies between different parts of the hand and different tasks. Changing object dimensions can thus lead to changes in overall grip comfort, as the areas of contact between the hand and object vary with grip.

Hand size should also be considered when determining the proper size for handheld devices in terms of grip comfort, strength, and preference. Kong and Lowe (2005) showed that perceived handle grip comfort was maximized at diameters (circumferences) of 37–44 (116–138) mm and 41–48 (129–151) mm for females and males, respectively. Lee et al. (2016) investigated grip comfort and postures, index finger reach areas, and muscle activations associated with different hand sizes, device widths, and tasks during index finger interactions on the rear areas of smartphone mock-ups. A greater width (90 mm) increased perceived grip discomfort overall; however, phones 60 mm wide were found to increase the muscle activation of the first dorsal interosseous for users with shorter hand lengths by a factor of approximately three relative to the 90 mm width, increasing the perceived discomfort by 12.3%. The necessity of accounting for hand size when determining smartphone size has, thus, been demonstrated.

Grip comfort during voice calls is critical for the overall smartphone grip comfort. A typical grip adopted during voice calls involves contact between the distal parts of the hand and side surfaces and/or edges: The thumb firmly contacts the lateral side and edges of the device while all or most of the remaining fingers or fingertips firmly contact the opposing lateral side and edges. As reviewed above, distal portions of the hand are more sensitive to pressure than proximal portions (Johansson & Vallbo, 1979, 1983), and the relatively high forces enacted on the narrow lateral sides and edges of the phone in this grip elevate the contact pressure on pressure-sensitive finger patches. In contrast, no firm grip is required for other smartphone tasks involving touchscreen interactions such as one- or two-thumb smartphone touch interactions. During these activities, the device lies loosely on the palm and the fingers instead, in rare cases receiving additional support from the little finger on the bottom or rear of the device (Lee et al., 2016). As touch interaction tasks do not require firm grips, grip comfort is less sensitive to the device form during these tasks relative to voice calls or hand-carrying tasks. Indeed, Yi, Park, Im, Jeon, & Kyung, (2017) demonstrated the variations in grip comfort between smartphones of different forms were more significant during voice calls than any other smartphone task (i.e., texting, watching videos, or viewing images), and the narrow lateral sides due to edge curvatures led to poor grip comfort during voice calls. Voice calling remains one of the most common smartphone tasks in South Korea (KISDI, 2014, 2015, 2017) and the United States (Fluent LLC, 2016; Gilbert, 2012; Hakernoon, 2017; Smith, 2015).

The objectives of this study were twofold: first, to investigate the effects of hand length, major dimensions (height, width, thickness, and edge roundness), and mass on the one-handed

TABLE 1: Participant Groups and Hand Lengths

	Stage	Short Hand (≤165.6 mm†)	Medium Hand (173.6–178.6 mm†)	Large Hand (≥186.6 mm†)	Total
Number of participants (male:female)	1	12 (0:12)	12 (6:6)	12 (12:0)	36 (18:18)
	2 and 3	12 (1:12)	12 (2:10)	12 (12:0)	36 (14:22)

†165.6 mm, 173.6 mm, 178.6 mm, and 186.6 mm correspond to 30th, 45th, 55th, and 70th percentiles, respectively, according to SizeKorea (2004).

grip comfort and attractiveness of smartphone designs, and second, to recommend corresponding smartphone dimensions and masses based on these results that can provide high grip comfort and design attractiveness. Grip during voice calls was given particular focus as it requires firmness rather than precision and involves the more sensitive distal parts of the hand. Three hypotheses were developed: Some dimensions influence overall smartphone grip comfort more strongly than others (hypothesis 1; H1), there exist interactive effects between smartphone dimensions (H2), and there is a suitable mass associated with a given smartphone size (H3).

MATERIALS AND METHOD

A three-stage study was conducted to determine the ranges of smartphone dimensions (height, width, thickness, and edge roundness) and mass associated with high grip comfort and design attractiveness. All three stages involved three hand-length groups. Stage 1 addressed H1 by determining the range of each dimension suitable for grip comfort and the relative strengths of their influences. Stage 2 addressed H2 by examining the main and interaction effects on grip comfort and design attractiveness of the influential dimensions identified in Stage 1. Stage 3 addressed H3 by varying the masses of smartphone mock-ups fabricated using the dimensions identified in Stages 1 and 2.

Participants

Thirty-six individuals (18 males and 18 females) participated in Stage 1, with a mean age of 22.3 years and standard deviation (*SD*) of 3.4 years. A separate set of 36 individuals (14 males; 22 females) with a mean age of 22.7 years (*SD* = 3.2 years) participated in Stages 2 and 3. All participants were recruited from a university population and had at least three years of smartphone use experience. All were right-handed and healthy without any musculoskeletal diseases affecting the wrist. Efforts were made to recruit individuals with a wide range of hand lengths (Table 1). All participants provided informed consent and were compensated for their time. The experimental protocol was approved by a local institutional review board.

Experimental Design

Hand length ($HL_{S/M/L}$; a between-subjects factor) was considered an independent variable and divided into three levels: HL_S (short hand length; ≤165.6 mm, 30th percentile), HL_M (medium hand length; 173.6–178.6 mm, 45th–55th percentile), and HL_L (large hand length; ≥186.6 mm, 70th percentile). The stated percentile values represent the hand lengths of persons 20–50 years old in the South Korean population (SizeKorea, 2004). These specific percentiles were selected to ensure a minimum difference of 5 mm in hand length between groups.

Stage 1 consisted of four sessions conducted to determine the ranges of four smartphone dimensions—height (P_{HT}), width (P_{WD}), thickness (P_{TH}), and edge roundness (P_{RN})—suitable for grip comfort and the relative strengths of their influence. In each session, one of the four dimensions was varied whereas the other three dimensions were fixed at the rounded mean values (P_{HT} = 140 mm, P_{WD} = 70 mm, and P_{TH} = 8 mm) of 52 smartphone models released in South Korea between 2013 and 2015 (P_{HT} = 144.1 mm, P_{WD} = 73.2 mm, and P_{TH} = 8.4 mm), and the P_{RN} was fixed at 2 mm (the midrange

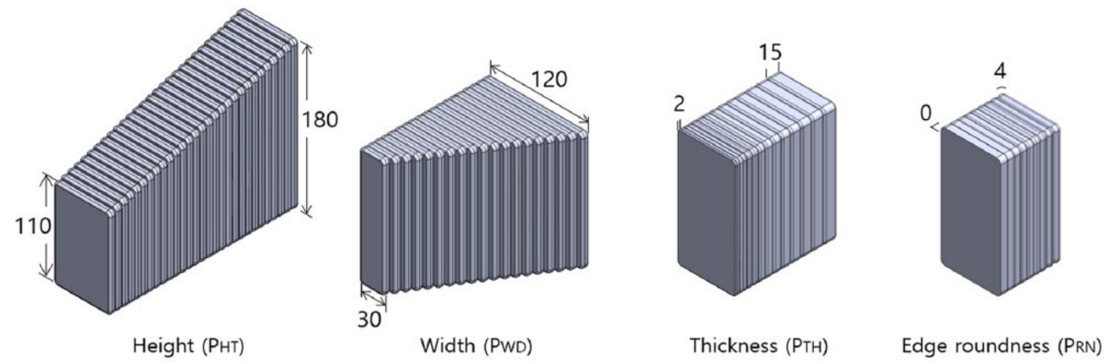


Figure 1. Mock-ups used in Stage 1. 29 P_{HT} levels (110–180 mm, 2.5 mm intervals), 19 P_{WD} levels (30–120 mm, 5 mm intervals), 14 P_{TH} levels (2–15 mm, 1 mm intervals), and 9 P_{RN} levels (0–4 mm, 0.5 mm intervals). One of the four dimensions was varied, whereas the other three dimensions were fixed (P_{HT} = 140 mm, P_{WD} = 70 mm, P_{TH} = 8 mm, and P_{RN} = 2 mm).

value of the 0–4 mm edge radius range feasible for the mean P_{TH}). This allowed the exploration of much wider ranges for the four dimensions than would have been possible otherwise. The grip comfort suitability of the manipulated dimensions was assessed. Based on the mean values of 52 smartphone models, 29 P_{HT} levels (110–180 mm, 2.5 mm intervals), 19 P_{WD} levels (30–120 mm, 5 mm intervals), 14 P_{TH} levels (2–15 mm, 1 mm intervals), and 9 P_{RN} levels (0–4 mm, 0.5 mm intervals) were considered in each session (see Figure 1). The P_{HT} session thus had a 3 (*HL*) × 29 (P_{HT}; within-subjects) mixed factorial design, the P_{WD} session a 3 (*HL*) × 19 (P_{WD}; within-subjects) mixed factorial design, the P_{TH} session a 3 (*HL*) × 14 (P_{TH}; within-subjects) mixed factorial design, and the P_{RN} session a 3 (*HL*) × 9 (P_{RN}; within-subjects) mixed factorial design. The session orders of presentation and factor levels were randomized.

Stage 2 identified the design dimension combinations that corresponded to high grip comfort and attractiveness by considering the main and interaction effects of P_{WD} and P_{TH}, the dimensions with the strongest grip comfort influence from Stage 1. The bivariate correlations between three types of grip comfort (grip comfort considering only phone width, grip comfort considering only phone thickness, and grip comfort considering overall dimensions) and between each type of grip comfort and design attractiveness were also examined. The values determined in Stage 1 were used for P_{HT} and P_{RN}, (P_{HT} = 140 mm and P_{RN} = 2.5 mm). The two values determined for P_{WD} in Stage 1 (65/70 mm) and 60 mm were used for P_{WD} ($P_{WD\text{-}S}/P_{WD\text{-}M}/P_{WD\text{-}L}$ = 60/65/70 mm). The value determined for P_{TH} in Stage 1 (P_{TH} = 8 mm) was used as a median level for P_{TH} ($P_{TH\text{-}S}/P_{TH\text{-}M}/P_{TH\text{-}L}$ = 7/8/9 mm), resulting in a 3 (HL) × 3 (P_{WD}; within-subjects) × 3 (P_{TH}; within-subjects) mixed factorial design. The effect of mass on grip comfort was minimized in Stages 1 and 2 by mounting a bar-shaped epoxy smartphone mock-up on a smartphone holder (OMT, South Korea; see Figure 2), to reduce the size–weight illusion (Charpentier, 1891: larger objects are perceived to be lighter than smaller objects, even if they are equal in mass). The mock-up orientation and height varied freely. Each participant grasped the mounted smartphone using a grip posture required during voice calls for 10 s with their right hand while seated on a fixed-height chair. Previous studies on grip force and comfort have considered task durations ranging from 3 s to 10 min (Dianat, Nedaei, & Nezami, 2015; Dong et al., 2007; Edgren, Radwin, & Irwin, 2004; Grant et al., 1992; Harih & Dolšak, 2013; Hur, Motawar, & Seo, 2012; Husain, Khan, & Hasan, 2013; Kong & Lowe, 2005; McGorry, 2001).

Stage 3 examined the effect of mass on grip comfort (GC_{MS}) by varying the masses of mock-ups fabricated using the dimensions determined in Stages 1 and 2 (P_{HT} = 140 mm, P_{WD} = 65 mm, P_{TH} = 8 mm, and P_{RN} = 2.5 mm). Considering a mass just-noticeable difference of 7%–10%

Figure 2. Smartphone mock-up mounted on a holder used in Stages 1 and 2 to minimize the effect of mass on grip comfort. (Holder clip could be moved freely to adjust mock-up angle, and the bottom was attached to the desk via suction.)

(Allen & Kleppner, 1992; Jones & Lederman, 2006), seven levels of phone mass (P_{MS}; a within-subjects factor) were defined from 106–198 g (the 1.5th and 98.5th percentiles, respectively) at 10% mean mass intervals, with the mean mass of the 52 sampled smartphone models (152 g) as the median level. Every participant used his/her right hand to grasp each of seven mock-ups placed on a desk without a holder and assumed a phone call grip posture for 10 s. There was a 5-min break time before the second repetition of each stage and between Stages 2 and 3.

Data Collection and Processing

Participants evaluated the grip comfort suitability of each dimension on a seven-point scale (e.g., for width 1: much too narrow, 2: too narrow, 3: a bit too narrow, 4: suitably wide, 5: a bit too wide, 6: too wide, and 7: much too wide) in Stage 1. In Stage 2, each participant responded to four questions on a seven-point scale regarding: (1) grip comfort based exclusively on phone width (GC_{WD}), (2) grip comfort based exclusively on phone thickness (GC_{TH}), (3) overall grip comfort (GC_{OV}), and (4) phone design attractiveness based exclusively on phone size (PD_{AT}). The descriptors for the first three questions were (1) very uncomfortable, (2) uncomfortable, (3) somewhat uncomfortable, (4) neutral, (5) somewhat comfortable, (6) comfortable, and (7) very comfortable, whereas those for phone design attractiveness were (1) very unattractive, (2) unattractive, (3) somewhat unattractive, (4) neutral, (5) somewhat attractive, (6) attractive, and (7) very attractive. In Stage 3, participants evaluated grip comfort on a seven-point scale similar to that described for Stage 2 but based exclusively on the mass (GC_{MS}). The elapsed times for Stages 1, 2, and 3 were 60, 40, and 20 min, respectively.

Data Analysis

All data from both repetitions were used in the analysis. For the grip comfort data obtained in Stage 1, a two-way mixed factor analysis of variance (ANOVA) (hand length and each dimension) was conducted. Further, the ratio of the suitable grip comfort range to the entire explored range was calculated for each dimension. A three-way mixed factor ANOVA (hand length, phone width, and phone thickness) was conducted for each of the three grip comfort data types (GC_{WD}, GC_{TH}, and GC_{OV}) and the design attractiveness (PD_{AT}) data obtained in Stage 2. The bivariate associations between the four dependent measures (GC_{WD}, GC_{TH}, GC_{OV}, and PD_{AT}) were also analyzed using the Pearson correlation coefficient. A two-way mixed factor ANOVA (hand length and phone mass) was conducted for the grip comfort data (GC_{MS}) obtained in Stage 3. When the ANOVA results showed significant main or interaction effects, post hoc pairwise comparisons were performed using Tukey's honestly significant difference (HSD) test. An additional comparison was performed between 52 smartphone models released in South Korea and 286 models released worldwide from 2013–2015 in terms of their mean and interquartile values to examine whether smartphone models for these two markets were different in size, and hence indirectly examine whether the results of this study could be generalized to other ethnic groups (note: this study considered only the young South Korean population). Additionally, the smartphone dimensions determined in this study were compared with the mean and quartile values of these two markets. All statistical analyses described above were performed using JMP™ (v11, SAS Institute Inc., Cary, NC), with significance defined as $p < .05$.

RESULTS

This section describes the ANOVA and post hoc test results from data obtained in each stage as well as the dependent variable correlations. The effect of *HL* was found to be nonsignificant ($p \geq .11$; Tables 2 and 3) for all dependent variables (i.e., the grip comfort and phone design attractiveness variables).

Determining the Range of Each Smartphone Dimension Suitable for Grip Comfort (Stage 1)

Table 2 shows the effects of hand length and each smartphone dimension on dimensional suitability for grip comfort. During single-dimension manipulation, P_{HT}, P_{WD}, P_{TH}, and P_{RN} significantly affected grip comfort dimension suitability ($p < .0001$). P_{HT} level 13 (140 mm) scored closest to the "suitable" device height of 4 (at 3.96), and ten levels (levels 8–18; 130.0–150.0 mm) belonged to the same group as level 13. P_{WD} level 9 (70 mm) scored closest to 4 (at 4.17), and three levels (levels 8–10; 65–75 mm) belonged to the same group. P_{TH} level 7 (8 mm) scored closest to 4 (at 4.00), and three levels (levels 6–8; 7–9 mm) belonged to the same group. P_{RN} level 6 (R = 2.5 mm) scored closest to 4 (at 3.97), and three levels (levels 4–6; 1.5–2.5 mm) belonged to the same group. The low suitable-to-overall-range ratios (11.1%–28.6%) shown in Table 2 indicate only narrow dimensional ranges provide grip comfort. P_{WD} and P_{TH}, with significantly narrower ratios (11.1% and 15.4%), appeared to influence grip comfort more strongly than other dimensions, supporting H1.

Device Width and Thickness and Their Interaction Effect on Three Types of Grip Comfort (Stage 2)

Table 3 shows the results of hand length, device width, and device thickness effects on grip comfort. When phone widths and thicknesses were manipulated simultaneously, the $HL \times P_{WD}$ interaction effect on GC_{WD} was significant ($p = .044$). Post hoc analysis results showed six additional treatments belonged to group A alongside the HL_S-65 mm condition, which exhibited the highest mean (*SD*) GC_{WD} of 5.3 (1.1). The HL_M and HL_L groups judged the 60 mm-wide mock-up to produce poor grip comfort, with HL_M-60 mm in group B and HL_L-60 mm in group C (the worst). The effect of P_{WD} on GC_{WD} was also significant ($p = .0002$), and post hoc analysis results showed only one width (70 mm) belonged to group A with the 65-mm width, which had the highest mean (*SD*) GC_{WD} at 4.9 (1.2). Although $HL \times P_{WD}$, $HL \times P_{TH}$, and $P_{WD} \times P_{TH}$ interactions all significantly influenced GC_{TH} ($p \leq .047$), post hoc analyses indicated that all the treatments belonged to the same group.

The $HL \times P_{WD}$ interaction significantly influenced GC_{OV} ($p = .028$). Six other treatments belonged to group A with HL_S-65 mm, which had the highest mean (*SD*) GC_{OV} of 5.2 (1.0). The 60 mm-wide mock-up was evaluated poorly by the HL_M and HL_L groups in terms of grip comfort (see Figure 3). Although the $HL \times P_{TH}$ interaction effect was also significant ($p = .001$), all treatments were placed in the same group during post hoc analysis. P_{WD} also demonstrated a significant effect ($p = .003$). The post hoc analysis showed that the 70-mm width belonged to group A with the 65-mm width, which had the highest mean (*SD*) GC_{OV} of 4.7 (1.2). Overall, the highest and second-highest grip comfort in terms of both GC_{WD} and GC_{OV} were commonly observed at P_{WD} = 65 mm and 70 mm, respectively. The effect of P_{WD} on PD_{AT} was significant ($p < .0001$), and the post hoc analysis showed that the 65-mm treatment belonged to group A with the 70-mm treatment, which had the highest mean (*SD*) PD_{AT} of 4.8 (1.4) (see Figure 4).

Associations Between Dependent Variables

The bivariate correlations between the four dependent variables used in Stage 2 were all positive and within a .34–.77 range (see Figure 5). GC_{OV} exhibited high positive correlations

TABLE 2: Effects of Hand Length and Each Smartphone Dimension on Grip Comfort Dimension Suitability

Phone Dimension Manipulated	Independent Variables	*p* Values	F Ratio	Partial η^2	Best Dimension (suitable dimension range for grip comfort [mm]; range ratios)
Height only	*HL*	.78	$F_{2, 33} = 0.25$	.015	—
	P_{HT}	<.001*	$F_{28, 924} = 126.77$	.793	140 (130.0–150.0†; 28.6%‡)
	$HL \times P_{HT}$	.11	$F_{56, 924} = 1.24$	.070	
Width only	*HL*	.19	$F_{2, 33} = 1.90$	.103	—
	P_{WD}	<.001*	$F_{18, 594} = 450.08$	.932	70 (65–75†; 11.1%‡)
	$HL \times P_{WD}$	.85	$F_{36, 594} = 0.64$	.037	
Thickness only	*HL*	.63	$F_{2, 33} = 0.47$	.028	—
	P_{TH}	<.001*	$F_{13, 429} = 273.49$	.892	8 (7–9†; 15.4%‡)
	$HL \times P_{TH}$	.42	$F_{26, 429} = 1.032$	.059	
Edge roundness only	*HL*	.74	$F_{2, 33} = 0.30$	.018	—
	P_{RN}	<.001*	$F_{8, 264} = 168.71$	.836	2.5 (1.5–2.5†; 25.0%‡)
	$HL \times P_{RN}$	.09	$F_{16, 264} = 1.52$	.084	

Note. *HL* = hand length, P_{HT} = phone height, P_{WD} = phone width, P_{TH} = phone thickness, and P_{RN} = phone edge roundness.
*$p < .05$.
†Range of dimensions in group A according to Tukey's HSD test.
‡Ratio of range suitable for grip comfort to entire explored range.

(.60–.77) with PD_{AT}, GC_{WD}, and GC_{TH}. PD_{AT} showed a high positive correlation with GC_{WD} ($r = .64$) but a low positive correlation with GC_{TH} ($r = .37$).

Determination of Phone Mass for One-Handed Grip Comfort (Stage 3)

Using the dimensions determined in Stages 1 and 2 [140 mm (H) × 65 mm (W) × 8 mm (T) × 2.5 mm (R)], the influence of mass on grip comfort (GC_{MS}) was analyzed using smartphone mock-ups varying only in mass. The effect of P_{MS} on GC_{MS} was significant ($p < .001$; Table 4), with P_{MS} being divided into four groups ($M_2M_1M_3$, M_3M_4, M_5M_6, and M_6M_7; see Figure 6). M_2 (122 g), M_1 (106 g), and M_3 (137 g) were suitable for grip comfort, with their mean (*SD*) GC_{MS} values being 5.3 (1.1), 5.2 (1.5), and 4.6 (1.2), supporting H3.

DISCUSSION

This study examined the main and interaction effects of hand length and smartphone specifications on grip comfort and design attractiveness. This section provides further comments on the obtained results and compares them to the results of previous studies. The limitations of the current study are also discussed.

The ranges of height and width which provided the high grip comfort in Stage 1 were described in Figure 7. The device dimensions that provided the best grip comfort in Stage 2, 140 mm (H) × 65 mm (W) × 8 mm (T) × 2.5 mm (R), are smaller than the mean dimensions of the 52 smartphone models released in South Korea between 2013 and 2015 [144.1 mm (H) × 73.2 mm (W) × 8.4 mm (T)] as well as the mean dimensions of 286 smartphone models released worldwide by the top five manufacturers during the same period [139.6 mm

TABLE 3: Main and Interaction Effects of Hand Length, Phone Width, and Phone Thickness on Three Types of Grip Comfort and Phone Design Attractiveness (PD_{AT})

		HL	P_{WD}	P_{TH}	$HL \times P_{WD}$	$HL \times P_{TH}$	$P_{WD} \times P_{TH}$	$HL \times P_{WD} \times P_{TH}$
GC_{WD}	*p* value	.55	<.001*	.62	.044*	.78	.10	.31
	F-ratio	$F_{2, 44}$ = 0.614	$F_{2, 66}$ = 10.074	$F_{2, 66}$ = 0.480	$F_{4, 66}$ = 2.594	$F_{4, 66}$ = 0.436	$F_{4, 132}$ = 2.063	$F_{8, 132}$ = 1.243
	partial η^2	.027	.234	.014	.136	.026	.059	.070
GC_{TH}	*p* value	.31	.19	.093	.047*	.009*	.026*	.92
	F-ratio	$F_{2, 44}$ = 1.222	$F_{2, 66}$ = 1.728	$F_{2, 66}$ = 2.466	$F_{4, 66}$ = 2.557	$F_{4, 66}$ = 3.670	$F_{4, 132}$ = 2.886	$F_{8, 132}$ = 0.407
	partial η^2	.069	.050	.070	.134	.182	.080	.024
GC_{OV}	*p* value	.20	.003*	.13	.028*	.001*	.20	.83
	F-ratio	$F_{2, 44}$ = 1.711	$F_{2, 66}$ = 6.313	$F_{2, 66}$ = 2.103	$F_{4, 66}$ = 2.913	$F_{4, 66}$ = 5.105	$F_{4, 132}$ = 1.330	$F_{8, 132}$ = 0.471
	partial η^2	.094	.161	.060	.150	.236	.039	.028
PD_{AT}	*p* value	.20	<.001*	.66	.17	.069	.39	.066
	F-ratio	$F_{2, 44}$ = 1.681	$F_{2, 66}$ = 14.105	$F_{2, 66}$ = 0.429	$F_{4, 66}$ = 1.656	$F_{4, 66}$ = 2.338	$F_{4, 132}$ = 0.886	$F_{8, 132}$ = 1.546
	partial η^2	.092	.299	.013	.091	.124	.026	.086

Note. Three types of grip comfort are GC_{WD} (considering only phone width), GC_{TH} (considering only phone thickness), and GC_{OV} (considering overall dimensions); PD_{AT} = phone attractiveness
*$p < .05$.

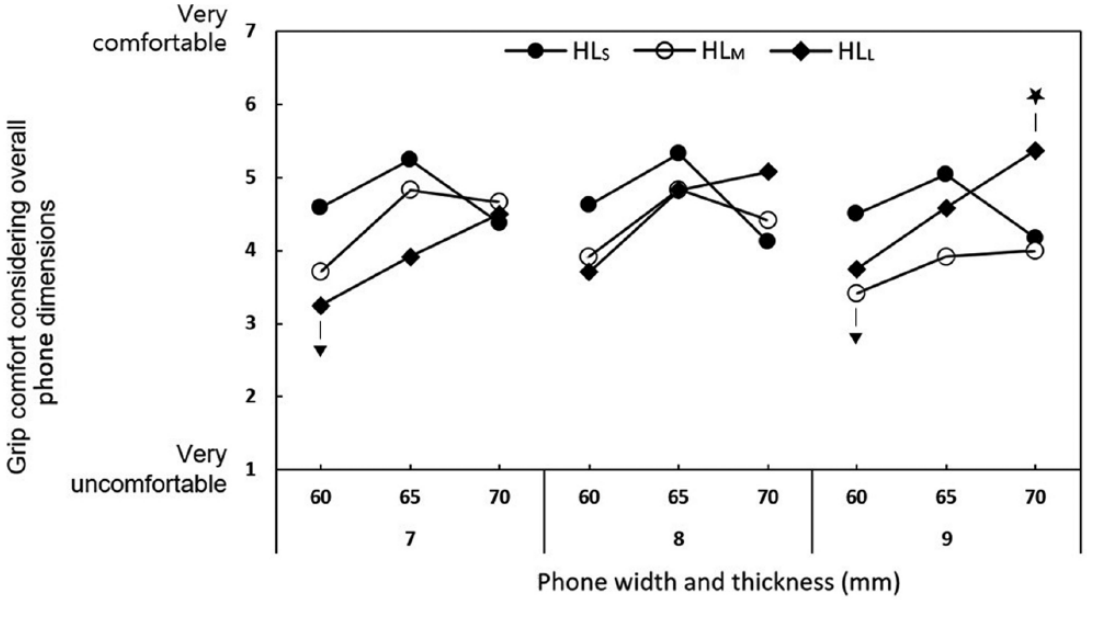


Figure 3. Effects of hand length, phone width, and phone thickness on grip comfort considering overall dimensions (★: highest grip comfort and in group A; ▼: not in group A according to Tukey's HSD test; *SD* range: 0.9–1.8).

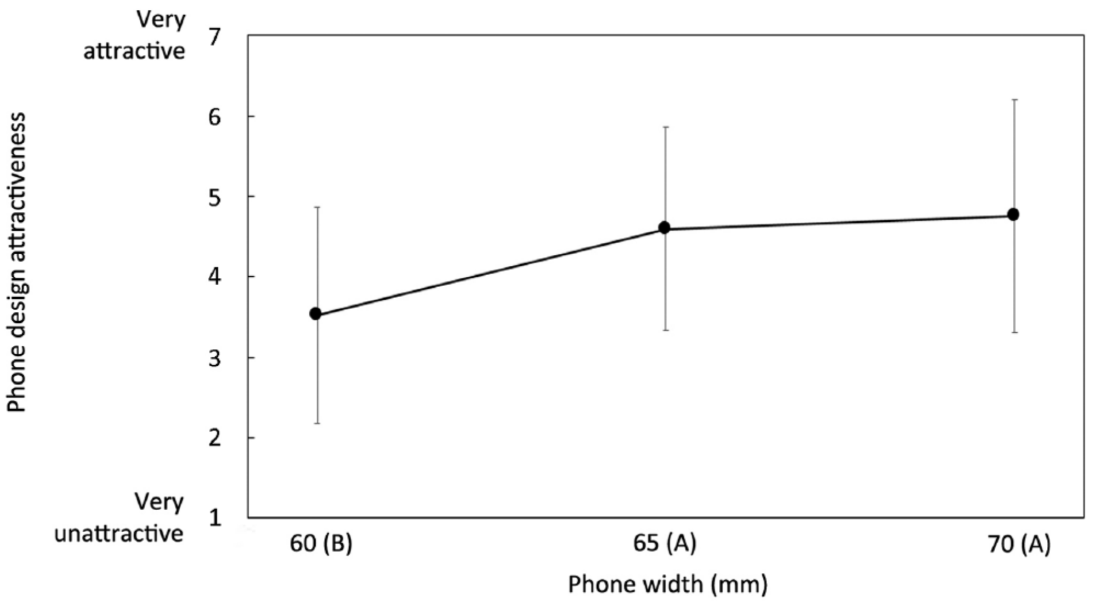


Figure 4. Effects of phone width on phone design attractiveness (Tukey's HSD grouping is indicated in parentheses; *SD* range: 1.3–1.4).

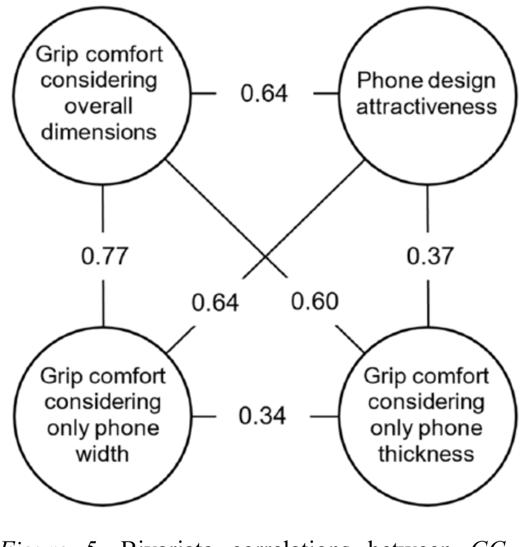


Figure 5. Bivariate correlations between GC_{WD} (grip comfort considering exclusively phone width), GC_{TH} (grip comfort considering exclusively phone thickness), GC_{OV} (grip comfort considering overall dimensions), and PD_{AT} (phone design attractiveness) (all p values $< .0001$).

(H) × 71.4 mm (W) × 9.2 mm (T)]. This suggests the mean dimensions of current smartphone devices are slightly too wide to provide one-handed grip comfort. A data comparison of the two markets showed they differed in terms of phone height ($p = .008$ for the unpaired t test), but not width ($p = .075$; see Figure 7). It should be noted that phone width was the most important dimension for grip comfort in the current study.

Grip comfort depended more strongly on phone width than thickness in the current study, supporting H1. The effects of P_{WD} on GC_{WD}, GC_{OV}, and PD_{AT} were significant in Stage 2; however, the effect of P_{TH} was not significant. Moreover, the bivariate correlations among GC_{OV}, GC_{TH}, GC_{OV}, and PD_{AT} were all positive (0.34–0.77), with GC_{OV} and GC_{WD} exhibiting the highest correlation ($r = .77$). In the P_{TH} range 7–9 mm, changes in phone thickness went unnoticed from a grip comfort perspective. The optimal width range for grip comfort ($P_{WD} = 65$–70 mm) was equal to the optimal width range for PD_{AT}. Additionally, GC_{OV} and PD_{AT} exhibited a high positive correlation ($r = 0.64$). Although the interaction effect of $P_{WD} \times P_{TH}$ on GC_{TH} was significant, the post hoc test showed all examined values were contained in a single group, partially supporting H2. The mean GC_{TH} was relatively high across phone widths of 60–70 mm (≥ 4.64) with thicknesses of 7–8 mm;

TABLE 4: Main and Interaction Effects of Hand Length (*HL*) and Phone Mass (P_{MS}) on Grip Comfort

	HL	P_{MS}	$HL \times P_{MS}$
p value	.19	<.001*	.15
F-ratio	$F_{2, 33} = 1.744$	$F_{6, 198} = 67.289$	$F_{12, 198} = 1.443$
partial η^2	.096	.671	.080

*$p < .05$.

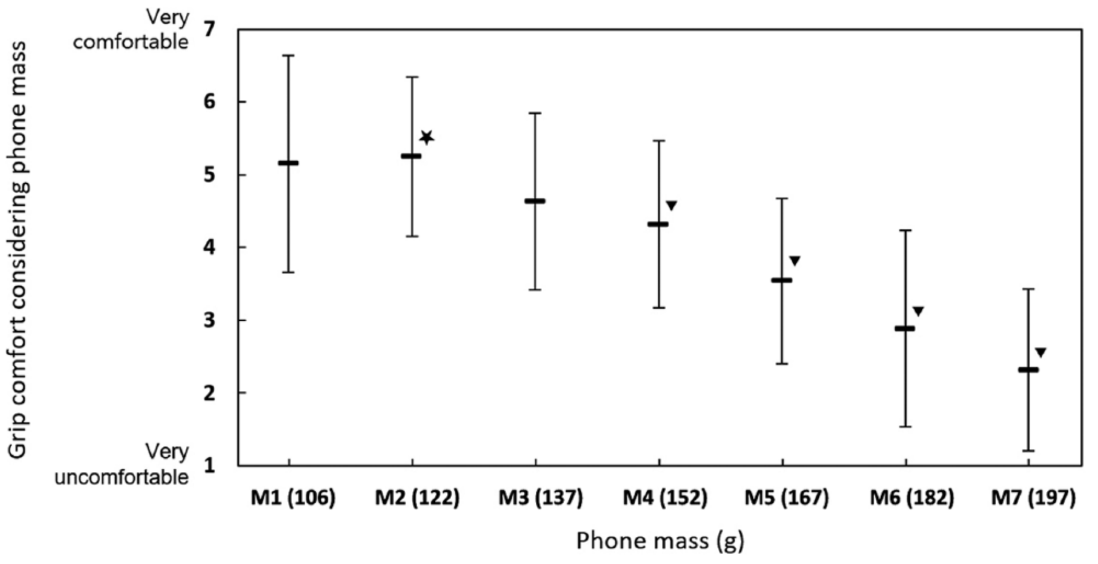


Figure 6. Effects of phone mass on grip comfort with phone dimensions fixed at 140 mm (H) × 65 mm (W) × 8 mm (T) × 2.5 mm (R) (★: highest grip comfort and in group A; ▼: not in group A; error bars indicate *SD*s).

however, it tended to decrease across phone widths of 60–65 mm (≤ 4.33) with thicknesses of 9 mm.

In this study, grip comfort and design attractiveness were evaluated in a multimodal context in which both haptic and visual information were presented together. As described above, the device width optimizing grip comfort (in which haptic information is of relatively greater importance) coincided with the width maximizing design attractiveness (in which visual information is of greater relative importance). These results indicate haptic and visual information complement each other and are both important in determining the grip comfort and design attractiveness of a smartphone. Indeed, Ernst and Banks (2002) demonstrated that people combined visual and haptic information to estimate object size more effectively. Similarly, Zhou, Niu, and Wang (2015) reported that operating comfort, determined by phone material, size, and shape, influenced perceived appearances as well as external factors such as shape attractiveness and layout rationality.

When using a handheld device, users select a grip posture considering the object, the task, and their hand (Cutkosky 1989, Lee et al. 2016). Previously, grasps have been classified by task or object characteristics. The classifications of Napier (1956) included “power grip” for stability and security, “precision grip” for sensitivity and dexterity, and “combined grip” (radial fingers positioned for precision grip and ulnar fingers for power). Cutkosky and Howe (1990) further divided the power and precision grips into nine and seven subcategories, respectively, considering object characteristics. Other grip postures include the “lateral pinch” (gripping an

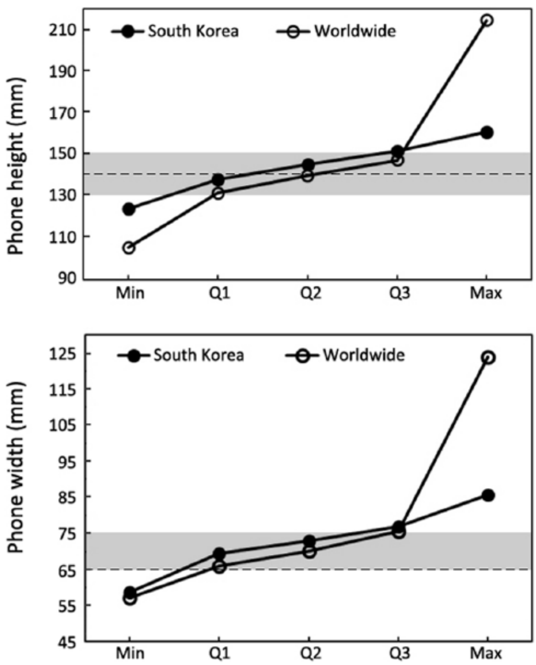


Figure 7. Comparison of height and width dimension min, max, and quartile values from 52 smartphone models released in South Korea and 286 models released worldwide between 2013 and 2015. Shaded areas are the ranges of device height and width to provide high grip comfort in Stage 1. Dotted lines indicate the dimensions of device height and width providing the highest grip comfort in Stage 2.

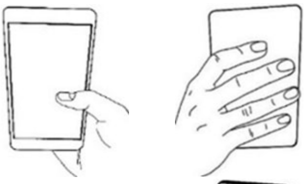
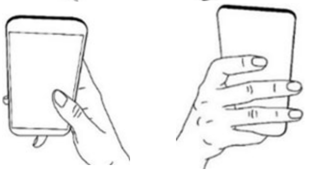
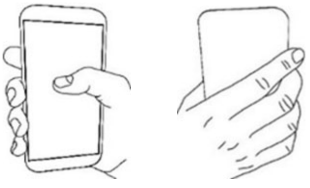
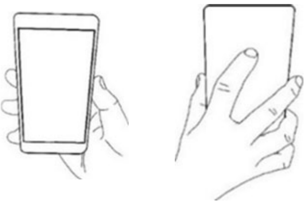
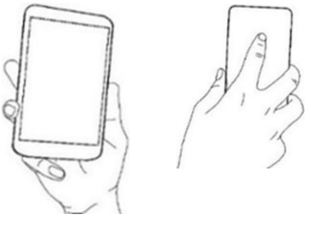
object with the thumb and index finger in a "power grip" position to make an additional motion such as spinning a key; Schlesinger, 1919; cited in Cutkosky & Wright, 1986), "dynamic grip" (interacting with an object using fingers while holding it such as pushing a button on a spray can; Kapandji, 1982), "precision handling" (extended metacarpophalangeal joints and flexed interphalangeal joints; Landsmeer, 1962), and "digital manipulative pattern" (a subcategory of precision handling; Elliott & Connolly, 1984). Smartphone grip postures also vary according to tasks (smartphone applications; Chang et al., 2006) and require a proper combination of power and precision to hold the device and achieve the intended interactions, resembling dynamic grips.

The calling task requires a firm grip and is critical in determining overall smartphone grip comfort. Lee et al. (2016) defined five types of one-handed smartphone grips (Table 5) differing by the contact regions between the glabrous hand skin and the device, the fingers involved, and the power- or precision-oriented nature. Among these five, the "holding lateral sides with fingers and thumb" grip resembles a typical voice call grip; however, the latter requires a firm and dynamic (e.g., for volume button control) grip. In the first three smartphone grip postures, the smartphone is laid on or loosely held by the hand while the thumb is used for touch interactions. Hence, these three grips (involving nonfirm dynamic grips) are less sensitive to smartphone dimensions relative to voice call (firm, dynamic) grips.

The previous studies on suitable widths or circumferences for handheld tools were conducted with respect to grip force or perceived comfort. Similar to current results, Chowdhury and Kanetkar (2017) reported the most preferred mobile phone width was 70 mm. Blackwell et al. (1999) found circumferences of 140–160 mm provided high grip force, whereas Kong and Lowe (2005) found cylindrical handles with circumferences of 116–151 mm provided maximal perceived comfort. These circumference ranges correspond to widths of 50–72 mm for an 8-mm-thick bar-shaped object. The overlapping range from both studies, 140–151 mm, likely provides both high grip force and perceived comfort. Smartphones 65 mm wide and 8 mm thick, or with a perimeter of 146 mm (= ((65W − 2 × 2.5R) + (8T − 2 × 2.5R)) × 2 + (2 × π × 2.5R)), provided the highest grip comfort in the current study. This value falls within the 140–151 mm range mentioned above, indicating that perimeters associated with high grip comfort are consistent across two object shapes (cylinder and parallelepiped).

The smartphone with the second-lightest mass (122 g) provided the highest grip comfort. This observation suggests a specific mass is associated with high grip comfort, supporting H3. Of note, the haptic perception of object masses can be affected by visually perceived object sizes: this size–weight illusion explains why larger object may be perceived as lighter than smaller objects even if they are equal in mass (Charpentier, 1891, as cited in Jones &

TABLE 5: Five Representative Grasp Postures Used for One-Handed Smartphone Front or Rear Interactions

Grasp Posture		Interaction Area	Digit Used for Interaction	Grasp Type	Contact Regions of Hand and Device
	Holding phone with fingers and palm	Front	Thumb	Nonfirm dynamic grip	Palm and fingers contact one lateral side and the rear.
	Supporting bottom with little finger	Front	Thumb	Nonfirm dynamic grip	Palm and fingers contact one lateral side and the rear while the little finger supports the bottom.
	Holding lateral sides with fingers, palm, and thumb	Front	Thumb	Nonfirm dynamic grip	Palm contacts one lateral side while the distal parts of all four digits (excluding thumb) contact the opposing lateral side.
	Holding lateral sides with fingers and thumb	Rear	Index	Firm dynamic grip	Thumb contacts one lateral side while the distal portions of the middle, ring, and small fingers contact the other side. Index finger touches the rear.
	Supporting bottom with little finger	Rear	Index	Firm dynamic grip	Thumb contacts one lateral side while distal parts of the middle and ring fingers contact the opposing lateral side and the little finger supports the bottom. The index finger touches the rear.

Note. Adapted and expanded from Lee et al., 2016.

Lederman, 2006). This study determined the smartphone dimensions and mass that provide the greatest one-handed grip comfort. Additional research will be required to determine the optimal mass for a smartphone design focused on screen size (e.g., a phablet) rather than one-handed grip comfort.

This study encountered several limitations. First, only the South Korean population was considered. Although South Korean adults with a wide range of hand lengths (14.5th to 92nd percentiles) were considered and the effect of hand length was not significant in this study, it is still necessary to verify whether the results of this study can be generalized to other ethnic groups or individuals with more extreme hand sizes. Second, this study considered only individuals in their 20s. As both tactile sensitivity and grip force of the hand decrease with age (Thornbury & Mistretta, 1981), older individuals are expected to be less sensitive to grip comfort; however, it remains necessary to examine whether grip comfort needs are altered in an older population. Third, although there may be diverse factors affecting the grip comfort and design attractiveness of smartphones, this study focused on only the major phone dimensions (phone height, width, thickness, edge roundness) and mass. The shape and location of screen curvature, for example, could also affect grip comfort (Yi et al., 2017). Fourth, the design attractiveness of a smartphone can be affected not only by the size of the device but also by various other factors such as color, novelty, brand, and other form factors (e.g., display ratio, button shapes and sizes, and materials; Chuang, Chang, & Hsu, 2001; Shinder, 2010; Hassan, 2015). Fifth, longer-term grips should also be considered: whereas this study investigated short-term grips, previous studies on grip comfort have used durations ranging from 3 s to 10 min. Although the 10-s grip duration used in this study is not too short, additional research is required to investigate longer-term grips. Sixth, it is necessary to investigate smartphone dimensions that provide high grip comfort for touch interaction tasks. However, in the case of the grip posture for touch interaction, the smartphone is laid on (or loosely held by) the hand while precise thumb movements are used for touch interactions. Because no firm grip is involved in this grip posture, non-extreme smartphone dimensions are less likely to affect grip comfort. Conversely, because a firm grip is required during voice calls, smartphone dimensions are more likely to affect grip comfort during voice calls (as demonstrated in this study). Finally, the findings of this study were based on subjective grip comfort and design attractiveness ratings. By the knowledge of these authors, no validated objective measurement for grip comfort has been reported in relevant literature. Neither Ahn, Kwon, Bahn, Yun, and Yu (2016) nor Lee et al. (2016) discovered significant associations between muscle activities and perceived discomfort, indicating muscle activities are insufficient for explaining physical discomfort. It is thus worthwhile to discover new objective measurements capable of effectively explaining grip comfort. Although future studies are necessary to address the above limitations, the findings of this study remain useful for improving one-handed smartphone grip comfort and design attractiveness.

CONCLUSION

This study involved the investigation of the effects of smartphone dimensions (height, width, thickness, and edge roundness) and mass on one-handed grip comfort and design attractiveness. The dimensions optimizing grip comfort and design attractiveness were 140 mm (H) $\times$ 65 mm (or 70 mm) (W) $\times$ 8 mm (T) $\times$ 2.5 mm (R) across three tested hand-length groups, and the most preferred mass was 122 g (from a range of 106–137 g). Width had the greatest influence on grip comfort and design attractiveness from the four investigated smartphone dimensions. In this study, a 146 mm horizontal perimeter was associated with high grip comfort and design attractiveness. This value lies in the middle of the cylindrical handle circumference range that has previously demonstrated high grip force and comfort (140–151 mm). These findings will contribute to the development of more ergonomic and aesthetically pleasing smartphones.

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KEY POINTS

- The influences of hand length, smartphone dimensions, and mass on grip comfort and design attractiveness were studied.
- Dimensions of 140 mm × 65 mm × 8 mm and 2.5 mm edge roundness are recommended.
- A mass of 122 g is recommended for recommended phone size.
- Phone width is a significant factor in grip comfort and design attractiveness.

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