Fingers' Range and Comfortable Area for One-Handed Smartphone Interaction Beyond the Touchscreen

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ABSTRACT

Previous research and recent smartphone development presented a wide range of input controls beyond the touchscreen. Fingerprint scanners, silent switches, and Back-of-Device (BoD) touch panels offer additional ways to perform input. However, with the increasing amount of input controls on the device, unintentional input or limited reachability can hinder interaction. In a one-handed scenario, we conducted a study to investigate the areas that can be reached without losing grip stability (*comfortable area*), and with stretched fingers (*maximum range*) using four different phone sizes. We describe the characteristics of the comfortable area and maximum range for different phone sizes and derive four design implications for the placement of input controls to support one-handed BoD and edge interaction. Amongst others, we show that the index and middle finger are the most suited fingers for BoD interaction and that the grip shifts towards the top edge with increasing phone sizes.

ACM Classification Keywords

H.5.2 User Interfaces: Ergonomics

Author Keywords

Finger range; comfortable area; one-handed; smartphone.

INTRODUCTION

Input controls such as power or volume buttons provide shortcuts to frequently used smartphone functions. These input controls extend touchscreen input and are accessible even without looking at the device. Manufacturers incorporate a wide range of additional input controls to support the increasing amount of functions on recent smartphones. Common examples include a dedicated button for the device assistant (*e.g.*, Samsung Galaxy S8), silent switches, fingerprint sensors, and even secondary screens on the device's rear (*e.g.*, Meizu Pro 7). Researchers also investigated additional input controls such as BoD touch panels [2, 12], edge squeezing [16, 43] and fingerprint sensors for gesture input [36]. Table 1 provides an overview of additional input controls.

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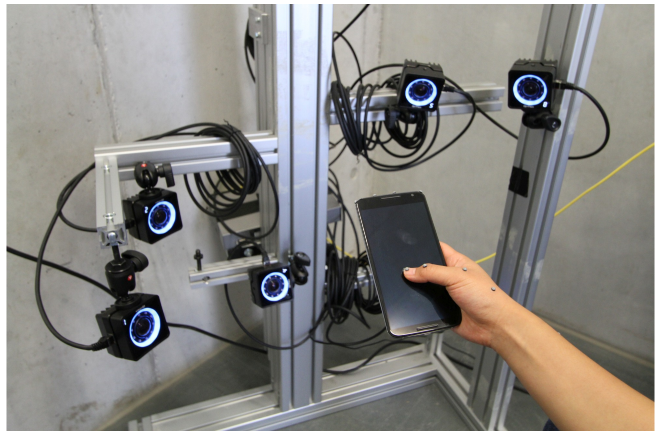


Figure 1. Participant exploring the comfortable area of the thumb on a Nexus 6 in front of an OptiTrack motion capture system.

While additional input controls provide clear benefits, they also pose new challenges. With the increasing amount of input controls around the phone, unintentional input can occur more frequently. Unintentional input can be avoided by placing input controls out of the hand's grip. However, not only unintentional input can be problematic but also the limited reachability of unfavorably placed input controls. As previous studies have shown that users prefer to use smartphones one-handed [19, 35], adding additional on-device input controls became even more challenging. Being forced to change the grip of the holding hand reduces the usability and can even lead to dropping the phone. While researchers and manufacturers explored a number of approaches to counteract these limitations (*e.g.*, Apple's Reachability, BoD interaction [22], gestures [52], and shortcuts to move the screen content [6, 20, 23]), they require additional actions from the users which also affects the usability and work only for touchscreens.

An important basis to design input controls for one-handed interaction is the analysis of finger movements that do not require a grip change. While Bergstrom-Lehtovirta and Oulasvirta [3] modeled the thumb's maximum range, there is neither previous work that does the same for all other fingers nor the area in which fingers can move without a grip change. Yoo *et al.* [54] explored the area in which the index finger can rest comfortably, but on a qualitative basis without moving the finger. However, the movement of fingers provide important implications for the design of on-device input controls. Specifically, they reveal the areas that users can reach without losing

Type \ Position	Front side	Back side	Top side	Bottom side	Left side	Right side
Touch	Fingerprint scanner Secondary screen [j] Hardware buttons (*e.g.*, back, home)	Fingerprint scanner BoD Touch [a,j] [2, 12] Heart rate sensor [f] [30] BoD touchscreen [m]	-	-	-	Edged touchscreen [b]
Buttons	Hardware keyboard [b] Home/Menu button [c] Back/Recent button [c]	BoD Button [d] Volume button [l]	Power button [e]	-	Volume buttons Bixby assistant button [f]	Power button Volume buttons Shutter button [g]
Slide switches	-	-	-	-	Silent switch [e]	-
Pressure sensors	Force Touch [53]	-	-	-	Side pressure [h] [16, 43]	
Scrolling	Trackball [i]	LensGesture [50]	-	-	-	Scrolling wheel [b]
Tapping	-	BoD taps [39]	Edge taps [31]			
Not intended for interaction	Front camera Front speaker Light sensor Distance sensor Notification LED	Back camera Back speaker Torchlight E-ink display [k]	Microphone Audio port USB port [g]	Microphone Speaker USB port Audio port	-	-

[a] OPPO N1, [b] RIM BlackBerry 8707h, [c] HTC Tattoo, [d] LG G-Series, [e] iPhone 5, [f] Samsung Galaxy S8,
[g] Nokia Lumia 840, [h] HTC U11, [i] Nexus One, [j] LG X, [k] YotaPhone 2, [l] Asus Zenfone, [m] Meizu Pro 7.

Table 1. Types of interaction controls beyond the touchscreen that are presented in prior work and in recent or past smartphones. While some are not intended for interaction initially (*e.g.*, camera), these sensors could still be used for interaction in the future, *e.g.*, [50].

grip stability, and the maximum range coverable by fingers without grip changes. Despite their relevance for the design of one-handed interaction, no previous work explored the areas and maximum ranges that all fingers can reach without grip changes using freeform tasks.

In this paper, we use a quantitative approach to empirically study the areas that can be reached without changing the hand grip and losing grip stability (*comfortable area*), and the range that can be covered with no grip change and stretched fingers (*maximum range*) while holding the smartphone one-handed in portrait mode. In a study, participants performed two tasks to explore the *comfortable area* and the *maximum range* on four smartphones with different sizes. We used smartphones with display sizes from $4''$ to $5.96''$ to make our findings generalizable beyond specific phone models. We recorded all finger movements using a high-precision motion capture system. Based on the results, we derive four generalizable design implications for the placement of on-device input controls that are suitable for one-handed interaction. These can increase the usability especially in scenarios where one hand is occupied. Amongst others, we found that the index and middle finger are the most suited ones for BoD interaction and that the grip shifts towards the top with increasing phone sizes.

The contribution of this paper is three-fold: On four different smartphones using a one-handed grip, we investigate 1. the *comfortable areas* that can be covered without changing the hand grip and losing grip stability; 2. the *maximum range* that can be covered without changing the hand grip and stretched fingers; and 3. four design implications for the placement of input controls to support one-handed smartphone interaction.

RELATED WORK

Since the contribution of this paper is an investigation of the fingers' reachability to inform the placement of on-device input controls, we review related work in two fields: (1) already existing on-device input controls on commercial smartphones and novel on-device input controls presented in previous work, and (2) studies of finger placements and movements while holding and interacting with a smartphone.

On-Device Input Controls

Previous work and manufacturers presented a broad range of input controls for smartphones of which we provide an overview in Table 1. We categorized them by their location on the device, and by the expected type of input.

Current smartphones such as the iPhone 7 and Samsung Galaxy S8 incorporate fingerprint sensors below the touchscreen or on the back of the device. These are mainly used for authentication purposes but can also recognize directional swipes that act as shortcuts for functions such as switching or launching applications. Previous work envisioned different functions that can be triggered using a fingerprint sensor [36]. Due to a small number of devices that support any form of interaction on the rear, researchers presented different ways to use built-in sensors for enabling BoD interaction, including the accelerometer [28, 39] to recognize taps and the back camera to enable swipe gestures [50]. Previous work also presented a number of smartphone prototypes that enable touch input on the whole device surface, including the front, back and the edges [24, 25, 33]. This enables a wide range of use cases which includes touch-based authentication on the rear side to prevent shoulder surfing [12], improving the reachability during one-handed smartphone interaction [22], 3D object manipulation [1, 41], performing user-defined gesture input [42] and addressing the fat-finger problem [2]. Recently, Corsten *et al.* [10] extended BoD touch input with a pressure modality by attaching two iPhones back-to-back.

Before HTC recently introduced Edge Sense, pressure as an input modality on the sides of the device have been studied in previous work [16, 18, 43, 46] to activate pre-defined functions. Legacy devices such as the Nexus One and HTC Desire S provide mechanical or optical trackballs below the display for selecting items as this is difficult on small displays due to the fat-finger problem [2]. As screens were getting larger, trackballs became redundant and were removed. Similarly, legacy BlackBerry devices incorporated a scrolling wheel on the right side to enable scrolling.

For years, smartphones featured a number of button controls. Amongst others, this includes a power button, the volume buttons, as well as hardware buttons such as the back, home and recent buttons on Android devices. As a shortcut to change the silent state, recent devices such as the iPhone 7 and OnePlus 5 feature a hardware switch to immediately mute or unmute the device. Moreover, the Samsung Galaxy S8 introduced an additional button on the left side of the device as a shortcut to the device assistant while other devices incorporate a dedicated camera button. Since a large number of hardware buttons clutter the device, previous work used the built-in accelerometer to detect taps on the side of the device [31].

Understanding and Modeling Hand Behavior

An important basis to inform the placement of on-screen interaction elements and on-device input controls is the analysis of areas on the device that can be reached by the fingers. Bergstrom-Lehtovirta and Oulasvirta [3] modeled the thumb's range on smartphones to inform the placement of user interface elements for one-handed interaction. To predict the thumb's range, the model mainly involves the user's hand size and the position of the index finger which is assumed to be straight (adducted). For the predicted range of the thumb, they introduced the term *functional area* which is adapted from earlier work in kinesiology and biomechanics. In these fields, possible postures and movements of the hand are called *functional space* [21]. Thumb behavior was further investigated by Trudeau *et al.* [45] who modeled the motor performance in different flexion states. Park *et al.* [37] described the impact of touch key sizes on the thumb's touch accuracy while Xiong *et al.* [51] found that the thumb develops fatigue rapidly when tapping on smaller targets.

Besides the thumb, previous work investigated the index finger during smartphone interaction. Yoo *et al.* [54] conducted a qualitative study to determine the comfortable zone of the index finger on the back of the device. This was done without moving the finger and by asking users during the study. From a biomechanical perspective, Lee *et al.* [27] investigated the practicality of different strokes for BoD interaction. Similarly, prior work found that using the index finger for target selection on the BoD leads to a lower error rate than using the thumb for direct touch [29, 48]. Wobbrock *et al.* [48] showed that both the thumb on the front and index finger on the BoD perform similarly well in a Fitts' law task. Wolf *et al.* [49] found that BoD gestures are performed significantly different than front gestures. Corsten *et al.* [9, 11] used BoD landmarks and showed that the rear position of the index finger could be accurately transferred to the thumb by pinching both fingers.

Since different grips can be used as an input modality [47], a wide range of prior work sought an understanding of how users hold the phone while using it. For example, Le *et al.* [26] investigated the static hand grip during common tasks on smartphones to derive new interaction possibilities from an ergonomic perspective. Similarly, Eardly *et al*. [13, 14] explored hand grip changes during smartphone interaction to propose use cases for adaptive user interfaces. They showed that the device size and target distance affects how much users tilt and rotate the device to reach targets on the touchscreen. Mohd Noor *et al.* [32] developed a model to predict subsequent touch locations on the front screen using the BoD finger placement. Further work on user interface adaptation include rotation based on hand grip [7], dynamic positioning of the keyboard [8], switching between modes [44] and launching applications [5]. Moreover, swipe errors can be detected based on finger movements on the back of the device [33].

Previous work in biomechanics looked into different properties of the hand. Napier *et al.* [34] investigated two movement patterns for grasping objects which they call *precision grip* and *power grip*. People holding objects with the *power grip* use their partly flexed fingers and the palm to apply pressure on an object. Sancho-Bru *et al.* [40] developed a 3D biomechanical hand model for *power grips* and used it to simulate grasps on a cylinder. However, as smartphones are not necessarily held in a power grip, this model cannot be applied to smartphone interaction. Kuo *et al.* [21] investigated the functional workspace of the thumb by tracking unconstrained motion. This is the space on the hand which is reachable by the thumb. Brook *et al.* [4] introduced a biomechanical model of index finger dynamics which enables the simulation of pinch and rotation movements. As holding a smartphone and interacting with the touchscreen introduces additional constraints to all fingers, these results cannot be applied to determine reachable areas and maximum finger ranges on smartphones.

Summary

In this paper, we study the movements of all fingers to derive design implications for on-device input controls. Thus, we provided an overview of already existing input mechanisms and showed that they are distributed across all except the bottom side. As previous work showed that users prefer one-handed interaction [19, 35], we reviewed related work on understanding and modeling finger ranges and placements on smartphones. In contrast to our work, previous work used predefined grips which is necessary for modeling the ranges but can lead to artificial grips that do not conform with the usual hand grip of users. Further, movements were only analyzed for the thumb while other fingers were studied during static placements (*e.g.*, [26, 54]). To understand the comfortable area and maximum range for deriving generalizable design implications, analyzing the fingers' movements is necessary.

DATA COLLECTION

We collected data about finger movements on smartphones using a high-accuracy motion capture system to analyze the areas that can be reached by the fingers. Specifically, we collected data on finger movements to analyze the *comfortable areas* and *maximum ranges* on four differently sized smartphones. Participants performed two tasks on four differently sized smartphones while holding the device one-handed without changing the hand grip.

Study Design

The study has two independent variables, PHONE and FINGER. For PHONE, we used four smartphones in different sizes (see

Table 2). For FINGER, we used all five fingers of the right hand. This results in a 4×5 within-subject design. We counterbalanced PHONE using a Balanced Latin square and used a random order for FINGER. For each condition, participants performed two independent tasks to explore the *comfortable area* and to determine the *maximum range*. During these tasks, they were seated in front of the motion capture system (see Figures 1 and 2a) on a chair without armrests. We did not instruct participants to use specific hand grips as this would influence the participant's usual hand grip and thus the generalizability of the study results.

Apparatus

Table 2 shows the four phones that were used. We specifically selected these devices to get a steady increase in device width as this dimension has a noticeable influence on the grip. In the remaining work, we will use the following abbreviations for the devices: *S3*, *S4*, *OPO* and *N6*. The *OPO* and *N6* are representative for recent large flagship smartphones (*e.g.*, Samsung S8 Plus, One Plus 5 or iPhone 7 Plus; on average 154% of the *S3*'s area) while the *S4* and *OPO* are representative for their standard versions (*e.g.*, Samsung S8, OnePlus X, or iPhone 7; on average 126% of the *S3*). The *S3* and *S4* are representative for small devices such as the iPhone SE, LG Nexus 5, or Sony Xperia Compact (on average 109% of the *S3*). While laser-cut device mockups could have been an alternative, we used real devices out-of-the-box to keep the participant's hand grip as realistic as possible. Due to a neglectable difference in device thickness (*SD*=1.0 *mm*), different device shapes (*e.g.*, edges and corners) should not affect the grip and finger movements as the edges are clamped between fingers and palm.

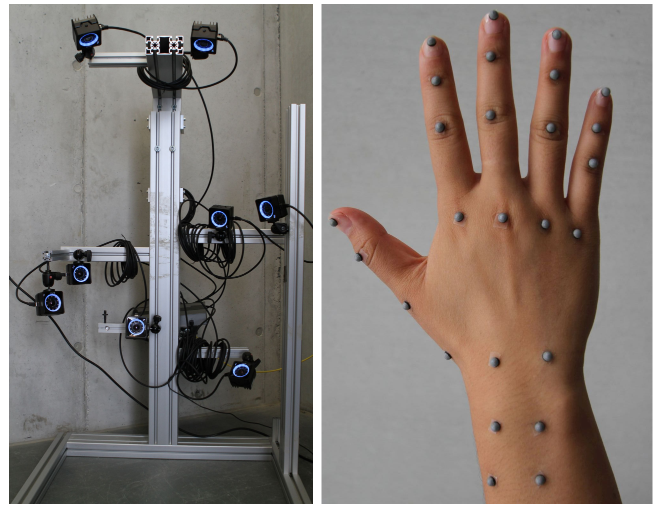
To record finger motions with sub-millimeter accuracy, we used an *OptiTrack* motion capture system with eight cameras (*OptiTrack Prime 13W* capturing at 240 *fps*). The cameras were firmly mounted to an aluminum profile structure as shown in Figure 2a. To enable these infrared cameras to record the finger movements, we attached 26 skin adhesive markers (4 *mm* hemispheres) on all joints of the hand similar to Feit *et al.* [15] as shown in Figure 2b. Additionally, we attached four markers on the top part of each smartphone which enables us to track the phones in six degrees of freedom (DoF).

Procedure

After participants signed the consent form, we collected demographic data using a questionnaire and measured their hand size and finger lengths. We then proceeded to attach 26 skin adhesive markers on their right hand to enable motion tracking. We handed out an instruction sheet explaining the procedure of the study and the two tasks which should be performed. The instruction sheet further explains three criteria that participants

device	abbr.	height	width	depth	area	%
Samsung Galaxy S3 mini	S3	12.16	6.30	0.99	76.61	100.0
Samsung Galaxy S4	S4	13.70	7.00	0.79	95.90	125.2
OnePlus One	OPO	15.29	7.59	0.89	116.05	151.5
Motorola Nexus 6	N6	15.93	8.30	1.01	132.22	172.6

Table 2. Sizes of smartphones (in *cm*) used in the study. The front and back surface area are shown in in cm^2 (width $\times$ height). The percentage column shows the increase in area starting from the S3.



(a) (b)

Figure 2. Study setup: (a) motion capture system consisting of 8 *OptiTrack Prime 13W* and (b) reflective markers on a participant's hand.

should fulfill while performing the tasks. This includes (1) holding the device one-handed (2) in portrait mode, and (3) not moving any finger except the one that the experimenter asks to move. We further gave participants a demonstration of the required movements and asked them to do it tentatively to ensure that everything is fully understood.

After handing a smartphone to the participants, we asked them to loosen and move their fingers on the device surface and hold the device as they would usually do afterward. To avoid influencing their usual grip after the experimenter hands out the device, we further asked participants to perform movements as if they would unlock the device with unlocking patterns to start using the device. In the first task, we collected data about the *comfortable area* of each finger. This is the area that one can reach without changing the hand grip and without losing the stable and firm grip through, *e.g.*, overstretching. We instructed participants to freely move the specified finger and cover all areas on the device that they can reach without changing the initial grip, losing grip stability or overstretching fingers to a degree which leads to straining the muscles. We further hinted that different finger flexion degrees should be probed to fill out the explored area and that they should continue exploring beyond the device surface (*e.g.*, beyond the top edge) if fingers can reach it comfortably.

In the second task, we investigated the finger's *maximum range*. This is the range that one can reach with a stretched finger while not changing the initial grip (*i.e.*, not moving any other finger). We instructed participants to keep the specified finger fully extended while performing an arc motion (*i.e.*, abduction and adduction) as far as possible without moving any other finger. Both tasks were repeated for all five fingers whereas the finger order was randomized. We decided to not randomize the task order as exploring the comfortable area involves free (and thus influenceable) movements in contrast to exploring the maximum finger range. While we gave participants 60 seconds to fully explore the comfortable area, the maximum finger range was explored for 30 seconds as there are fewer DoF to explore. The experimenter monitored the markers throughout the study to ensure that only one finger was moving while all others were not. The study including optional breaks took 40 minutes on average.

Participants

We recruited 16 participants (7 female) through our university mailing list. Participants were between 19 and 30 years old (M = 23.5, SD = 3.5). All participants were right-handed with hand sizes between 163 mm and 219 mm (M = 184.1 mm, SD = 17.1) measured from the tip of the middle finger to the wrist crease. Our collected data comprise samples from the 5th and 95th percentile of the anthropometric data reported in prior work [38]. Thus, the sample can be considered as representative. We reimbursed the participants with 10 EUR.

PREPROCESSING

The goal of the preprocessing step is to assign unique identifiers to the markers and convert them from 3D to 2D space (*i.e.*, front side for thumb markers, rear side for all others).

Labeling and Cleaning Data

We labeled all markers using semi-automatic labeling provided by OptiTrack's *Motive:Body* software. We used the *Fragment/Spike* option (Max Spike= $5\,mm/frame$; Max Gap= $10\,frames$) which followed the trajectory until a gap or a spike in marker movement was found. These settings were chosen to prevent marker swaps in the trajectory. We removed all frames in which the phone's rigid body was not tracked due to technical issues. These issues can occur as each of the four markers of the rigid body need to be captured by at least three cameras to be reconstructed. We further applied a heuristics to detect erroneous rigid body tracking by assuming that the phone was not held in uncommon poses (*e.g.*, up-side-down, flipped). In total, we removed 2.1% of all recorded frames.

Generating 2D Heatmaps

To transform recorded 3D movements onto 2D planes (front and back side), we transformed each hand marker from the global coordinate system into the device's coordinate system and projected them onto the device surfaces. Movements on the device surfaces are represented by heatmaps with a raster size of $1\,mm \times 1\,mm$. Due to a fixed duration and capture rate during the tasks, the number of data points on the heatmaps represents the frequency in which the respective locations were covered by the finger. We validated the transformation by sampling five frames per participant which we manually checked for correctness.

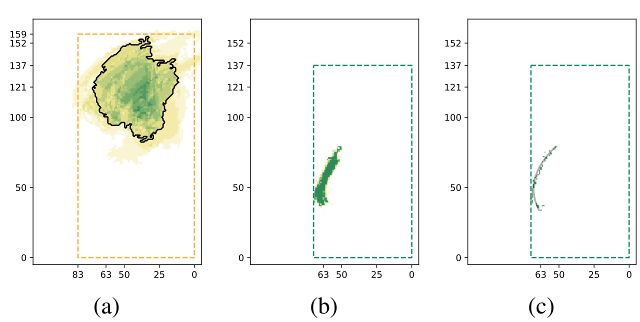


Figure 3. **(a) Comfortable area of the index finger on an N6. Black contour shows the area explored by at least 25% of participants; (b) raw recording of the maximum range task of an index finger on the S4; (c) maximum range after preprocessing and curve fitting (black curve).**

Determining the Comfortable Area

We used the markers placed on the fingertips to determine the comfortable area for interaction. We first filtered noise in each heatmap by removing all data points with a sum less than 10 in a 5×5 neighborhood (*i.e.*, all spots explored less than 41.6 ms at 240 fps). Using dilation and erosion on a binary version of the heatmap, we then filled little gaps within the comfortable area. Since heatmaps are now binary, the results for each participant were added up to retrieve a heatmap representing all explored spots normalized over participants (see Figure 3a). To remove spots that are only reachable to a small number of participants due to an outstanding hand size or convenient grip, we removed all spots which are not explored by at least 25% of all participants to exclude outliers.

Determining the Maximum Range

We applied the same noise removal procedure as described above. We then retrieved the farthest data points into each direction starting from the bottom right corner of the device and omitted all other points. This removes accidental touches or touches with a finger that was not fully stretched (see Figures 3b and 3c). Using the farthest points, we fitted a quadratic function to describe the finger's maximum range. Bergstrom-Lehtovirta and Oulasvirta [3] showed that the thumb's maximum range can be described by quadratic functions (reported average $R^2 = .958$). We will show that this is also possible for all other fingers with a high R^2. To reproduce their approach, we fitted the same quadratic function $f_{a,h,k}$ to the filtered data also using non-linear regression and a least-squares approach. In contrast to their study, our participants were free to hold the phone in any grip they were used to. As a specific grip could not be assumed, we had to include the rotation of the phone in the hand into the fitting process. We therefore introduced a rotation matrix R_α resulting in the function $g_{a,h,k,\alpha}$ as shown in Equation (3):

$$f_{a,h,k}(x) = a(x+h)^2 + k \tag{1}$$

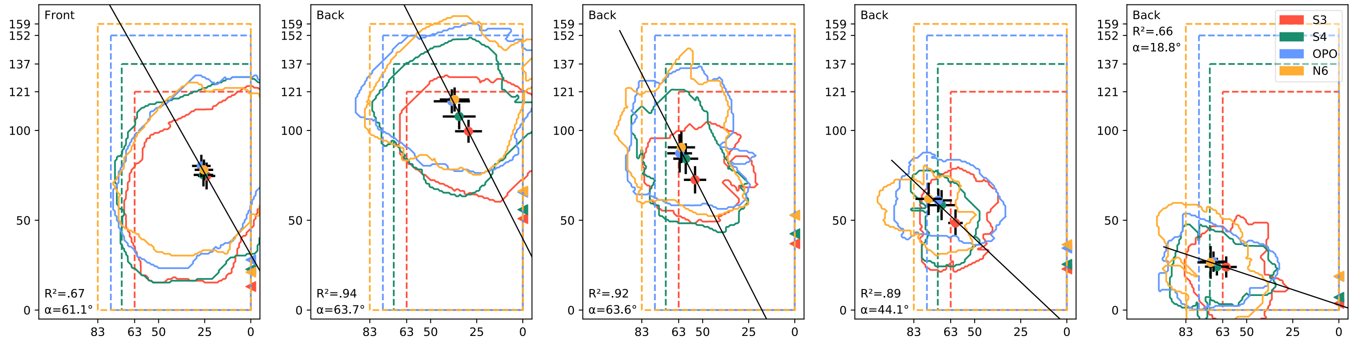
$$R_\alpha = \begin{pmatrix} cos(\alpha) & -sin(\alpha) \\ sin(\alpha) & cos(\alpha) \end{pmatrix} \tag{2}$$

$$g_{a,h,k,\alpha}(x) = R_\alpha \cdot \begin{pmatrix} x \\ f_{a,h,k}(x) \end{pmatrix} \tag{3}$$

The corresponding error function e which we used to find the parameters a, h, k and α is:

$$e_{a,h,k,\alpha}(p) = f_{a,h,k}(r_x) - r_y \text{ with } r = R_\alpha^{-1} \cdot p \tag{4}$$

The range of g in which finger movements are restricted in abduction and adduction movement is then obtained from the minimum and maximum value in x direction of the filtered data after rotating by R_α. To finally retrieve the average maximum range of each finger over all participants, we calculated the mean function over x for all $g_{a,h,k,\alpha}(x)$ of each participant.



(a) Thumb (F_0) (b) Index finger (F_1) (c) Middle finger (F_2) (d) Ring finger (F_3) (e) Little finger (F_4)

Figure 4. Contours of the comfortable areas averaged over participants for all fingers. Dots indicate the area's centroid with whiskers indicating the standard deviation. Black line visualizes the areas' shift with angle α towards the upper left corner with increasing device sizes. Triangles on the right show the average y-position of the respective finger's MCP joint and thus describing the grip. Device sizes are indicated by dashed lines and ticks in *mm*. Movements of the thumb took place on the front side while all other movements were on the back side.

RESULTS

To facilitate the notation, we will use the abbreviations F_0 to F_4 for the thumb to the little finger respectively. To report values for each finger at once, we use square brackets containing the values starting with F_0 (*e.g.*, [F_0 F_1 F_2 F_3 F_4]). We mapped the origin $(0,0)$ of all figures to the bottom right corner of the smartphone.

Comfortable Area

Figure 4 depicts the contour of the comfortable area for all fingers. The color of the contours denotes the device while dashed lines represent the size of the respective device.

Area size

Table 3 shows the size of the comfortable area for each finger on the four devices. Between the devices, there is a linear growth of the comfortable area with increasing device sizes for the index and the middle finger. We performed a Pearson's correlation test to test for a significant correlation between the device's diagonal length and the size of the comfortable area. We found a significant correlation for the index and the middle finger (r = [−.303 .975 .985 .311 .699], p = [.697 .025 .015 .689 .301]). This correlation can be described as a linear behavior with an average fitness of R^2 = [.09 .95 .97 .10 .49].

Area positions

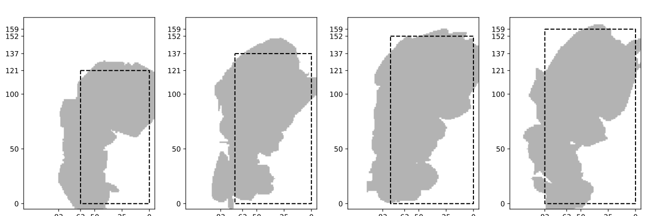
The dots in Figure 4 represent the area's centroid position averaged over all participants. Attached whiskers represent the standard deviation. The centroids are gradually shifting towards the upper left edge with increasing sizes of the smartphone. This shift can be described by a linear function with a fitness of R^2 = [.67 .94 .92 .89 .66] for all five fingers. This suggests that the index, middle and ring finger are linearly shifting towards the left edge with increasing device sizes. Pearson's correlation test revealed a correlation between the device's diagonal and a gradual shift of the index, ring and little finger towards the top left corner (r = [.818 .974 .962 .956 .983], p = [.182 .026 .038 .044 .017]).

Union of BoD comfortable areas

We show the union of the comfortable areas for the back side in Figure 5. Hereby, they show that 68.8 % of the *S3* can be reached without changing the grip or losing stability, while this is the case for 67.3 % for the *S4*, 73.4 % for the *OPO* and 67.7 % for the *N6*.

Maximum Finger Range

The bold quadratic curves in Figure 6 describe the maximum range reachable by each finger averaged over all participants. The dotted curves represent the standard deviations from the mean curve in bold. Bergstrom-Lehtovirta and Oulasvirta [3] showed in prior work that the thumb's maximum range can be described by quadratic curves (reported average R^2 = .958). They tested this by fitting a quadratic curve into each thumb trajectory made by participants. We performed the same test for the finger range heatmap for our participants to test whether the maximum range of other fingers can be described by quadratic curves. Our test yielded an average fitness of R^2 = [.91 .96 .99 .93 .96] indicating that the maximum range of other fingers can also be described through quadratic curves.

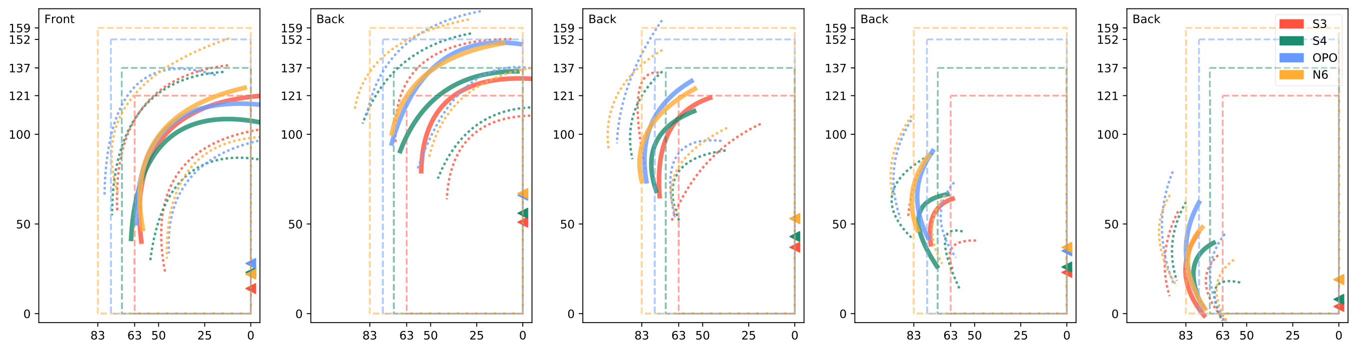


(a) S3 (b) S4 (c) OPO (d) N6

Figure 5. Union of comfortable areas of all fingers on the BoD.

	S3	S4	OPO	N6	Mean	SD
Thumb - F_0	33.6	41.9	35.2	35.0	36.4	3.3
Index Finger - F_1	30.8	37.3	48.9	47.6	41.1	7.5
Middle Finger -F_2	24.6	28.5	35.3	36.7	31.3	5.0
Ring Finger - F_3	15.8	11.7	18.0	22.0	16.9	3.7
Little Finger -F_4	16.9	16.0	20.5	23.7	19.3	3.1
BoD Union (F_1 - F_4)	79.7	88.6	109.6	106.7	96.2	14.4

Table 3. Comfortable areas in cm^2 for all fingers on four devices.



(a) Thumb (F_0) (b) Index finger (F_1) (c) Middle finger (F_2) (d) Ring finger (F_3) (e) Little finger (F_4)

Figure 6. These figures show the maximum range for all fingers on four different devices when fully stretched. Bold quadratic curves represent the mean range, while the dotted curves show the ranges one standard deviation further from the mean. Triangles on the right show the average y-position of the respective finger's MCP joint. Device sizes are indicated by dashed lines and ticks in *mm*. Movements of the thumb took place on the front side while all other movements were on the back side.

Effect of Grip and Hand Sizes

We investigated the effect of hand sizes on the common comfortable area by dividing the data into three balanced sets: *Small hands* ($< 17.5\,cm$), *medium hands* (between $17.5\,cm$ and $20.0\,cm$), and *large hands* ($> 20.0\,cm$).

The way a user holds the device influences the position of the comfortable area and the maximum range (see Figure 7). For the four device sizes, we observed the index finger's *metacarpophalangeal joint* (MCP) which is the joint between the finger and the hand bones. The y-position of this joint indicates the position along the height of the device and thus how high users held the phone, starting from the bottom edge of the phone. Their y-positions are depicted as triangles in Figure 4. A one-way ANOVA reveals a significant difference in the y-position of the index finger's *MCP* between four different device sizes, $F_{3,271} = 23.518$, $p < .001$. Bonferroni post hoc tests revealed significant differences between *S3* and *S4* ($p = .002$), *S3* and *OPO* ($p < .001$), *S3* and *N6* ($p < .001$), *S4* and *OPO* ($p = .004$) as well as *S4* and *N6* ($p < .001$).

Figure 7a shows the comfortable areas of participants with small hands. Even within a hand size group, the positions of the comfortable areas can be different. Thus, we calculated the average variance (a) between the centroids within groups of hand sizes and (b) between the centroids of all participants as a measure for the spreadness of the comfortable areas. We tested whether there is a significant difference between the average variances of these two groups. A Welch's t-test revealed that the variance for group a ($M = 14.8$, $SD = 8.1$) was significantly different from group b ($M = 16.2$, $SD = 8.3$), $t_{545.82} = 2.055$, $p = .040$. This shows that the variance between the centroids of the comfortable area can be decreased by $1.4\,mm$ on average when splitted into hand size groups.

DISCUSSION

To help designing one-handed BoD and edge interaction, we conducted a study to record finger movements on smartphones using a high-precision motion capture system. We focused on the area that is reachable without changing the hand grip and losing grip stability (*comfortable area*) and the range that is reachable without a grip change (*maximum range*) for all five fingers on four different smartphone sizes.

The results show that the upper half of the smartphone's rear is comfortably reachable by the index and middle finger (see Figure 5). This conforms with findings from previous work on BoD interaction [22, 42, 48], and the placement of fingerprint sensors on recent commercial devices (*e.g.*, Google Pixel, LG G6). The ring and little finger can reach the lower left quarter of the device while the lower right quarter is covered by the palm or parts of the fingers close to the palm (*i.e.*, *proximal phalanges*). Thus, the lower left quarter is not reachable by any finger without a grip change. We further showed that the comfortable areas of the index and middle finger are larger than the counterparts of the ring and little finger. This indicates that both ring and little fingers are less flexible when grasping the device. While the ring finger can only be moved individually to a lesser extent [17], the little finger is required to support the grip from the bottom side or stabilizing on the left side.

With increasing device sizes, we found that the comfortable areas of the index and middle fingers significantly increase. This conforms with the observation of higher flexibility described above as these fingers can fully explore the increasing rear surface. We also observed that the hand grip, indicated by the positions of the *metacarpophalangeal joint*s (MCPs), move towards the top with increasing device sizes. A possible explanation for this shift is that users try to balance the device's vertical center of gravity by moving the grip towards the top with increasing device height. The shift in hand grip, in turn, affects the centroids of the comfortable areas that shift towards the top left corner of the device. Similarly, the shift of the comfortable area towards the left side can be explained by the balancing of the horizontal center of gravity.

Extending the previous work by Bergstrom-Lehtovirta and Oulasvirta [3], we showed that quadratic functions combined with a rotation also enable to describe the maximum range of all fingers with an average $R^2 = .95$. This rotation is necessary as users hold the device in slightly different angles. Conforming

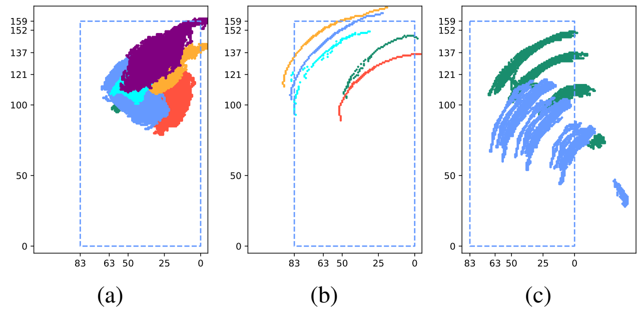


Figure 7. For the N6 and the index finger, (a) a set of comfortable areas of participants with small hands, (b) a set of preprocessed maximum ranges of participants with medium hands, and (c) raw maximum ranges for all index finger joints of P5 and P15 with different grips (blue: little finger supporting device's bottom; green: little finger grasping the edge).

the comfortable areas, the maximum ranges show that the upper left corner is not reachable without a grip change. With increasing device sizes, the maximum range moves towards the top left corner similar to the centroids of the comfortable areas. This is caused by the hand grip's shift towards the top edge. Still, the gap between the maximum range and the upper left corner of the device also increases for larger devices and cannot be reached without a grip change.

We investigated and reported the average maximum range of all fingers and the comfortable areas that are reachable by at least 25% of all participants (to exclude outliers). These help smartphone designers to find suitable locations for additional input controls that can be operated one-handedly by a wide range of users. We also reported the variance within the set of participants which were caused by different hand sizes and grips. This variance decreases significantly when looking at different groups of hand sizes separately. Since the majority of smartphones are not produced for a specific hand size group, we presented the variance as an outlook to future work as a separate analysis for different hand size groups would go beyond the scope of this work.

DESIGN IMPLICATIONS FOR INPUT CONTROLS

Based on the comfortable areas and maximum ranges, we derived the following design implications for one-handed interaction on the back of the device. Specifically, we focus on informing the placement of additional input controls to enable users to operate them one-handedly without changing their hand grip or overstretching fingers which could lead to dropping the device.

Do not place input controls on the bottom right. The bottom right quadrant on the back of the device is not reachable for any of the four fingers on the back without a grip change. When holding a phone, this area is also covered by the hand's palm. Hence, no input controls should be placed at the bottom right corner of the device to avoid grip changes and unintentional input.

Place input controls within the comfortable area. Fingers can move freely within the comfortable area without grip changes or losing grip stability. The majority of the comfortable area is located on the upper half of the device's rear and reachable by the index and the middle finger. To avoid dropping the device and muscle strains, input controls should be placed so that interaction takes place within the comfortable area.

Use the index finger for complex and frequent BoD input. The index finger has the largest comfortable area on the back side of all four devices due to its flexibility. Complex and frequent movements such as BoD gestures and location-dependent tapping (*e.g.*, fingerprint scanners) benefit from this flexibility and should be performed with the index finger.

Place input controls higher on larger devices. We found that both the comfortable areas and the average position of the finger's MCP are shifting towards the top edge of the device with increasing devices sizes. This indicates that users are holding the device higher the larger the device is. Thus, we recommend to place input controls higher for larger devices, including buttons on the left and right edges.

LIMITATIONS

We collected empirical data to determine the maximum ranges and comfortable areas of right-handed participants who used the dominant hand to hold the smartphone. While the data of left-handed participants could look similar to the data of right-handed participants due to anatomical reasons, we could not neglect the effect that left-handed participants could have re-learned and adapted their usual grip to common user interfaces which are optimized for right-handed users (*e.g.*, sending button in messengers and switches in setting screens are on the right side). Thus, it is left for future work to investigate differences between both user groups. While we focused on one-handed interaction in portrait mode, we did not consider potential effects on other grips such as two-handed interaction or when holding the device in landscape mode.

Moreover, we intentionally did not instruct participants to hold the devices with specified grips. Limiting the number of degrees of freedom such as the hand grip can lead to artificial behavior that does not conform to how users generally hold and interact with a smartphone. Since our contribution focuses on a set of generalized design implications for input controls that can be used one-handed, it was necessary to allow adequate degrees of freedom to avoid affecting the usual hand grip of our participants.

CONCLUSION & FUTURE WORK

In this paper, we investigated the areas which are reachable without changing the hand grip or losing grip stability (*comfortable area*) and the coverable range when fingers are fully stretched (*maximum range*). We conducted a lab study in which participants were recorded by a high-precision motion capture system while performing finger movements on four differently sized smartphones. We presented the average maximum range and the comfortable area which can inform the design of one-handed interaction on the back and edge of the device for a wide range of smartphone sizes.

Based on the results, we derived four design implications that can help designers to place input controls so that users can interact with them one-handedly. Particularly, they help to find suitable placements of input controls that do not require a change of hand grip or a loss of grip stability which could lead to dropping the device or muscle strain. Amongst others, the key findings include using the index and middle finger for Back-of-Device (BoD) interaction since they are the most flexible fingers and the shift of the hand grip towards the top edge with increasing device sizes.

While we derived common design implications for one-handed smartphone interaction, future research should follow up on our analysis on the impact of different hand sizes on the finger range and comfortable area. Resulting findings could be used to propose design implications for specific hand sizes (*e.g.*, smartphones for children). Moreover, the comfortable area and maximum range can be explored for specific types of input controls. While touching a button is usually done with an angled finger, fingerprint scanners require a flat placement of the finger. Investigating one specific type of input control would limit the result's generalizability due to constraints such as specific finger angles. However, the results can be more precise when only a certain type of input control is used.

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