One-Handed Bend Interactions with Deformable Smartphones

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ABSTRACT

Smartphones are becoming larger, mainly because bigger screens offer a better experience for viewing content. One drawback of larger screens is that they make single-hand interactions difficult because of hard to reach touch targets and of the need to re-grip the device, both factors significantly reducing their usability. Flexible smartphones offer an opportunity for addressing this issue. We first set out to determine the use of common single-hand mobile interactions through an online survey. Then, we designed and evaluated one-handed deformable gestures that offer the potential for addressing the finger reach limitation on large smartphones. We identified that the top right up bend and the center squeeze up gestures are the fastest and preferred gestures. We found no hand preference, which indicates that the gestures could be implemented to fit the needs of a wider range of the population, instead of favoring right-handed users. Finally, we discuss the impact on deformable gestures on one-handed interactions issues.

Author Keywords

Deformable user interfaces; flexible displays; one-handed interactions; bend gestures; mobile; HCI;

ACM Classification Keywords

H.5.2. Information interfaces and presentation: *User Interfaces – Interaction styles, user-centered design.*

INTRODUCTION

Large screen smartphones are becoming increasingly popular in the mobile phone arena, mainly because larger screens offer a better experience for viewing content. One drawback of larger screens is that they make single-hand touch interactions more difficult as they significantly limit the reach of the interacting finger(s) [4,9,12,29]. Single-hand interactions are performed using one hand which both holds and interacts with the device, as opposed to gestures performed while the device is on a table. Figure 1 illustrates a typical case for one-handed touch interactions.

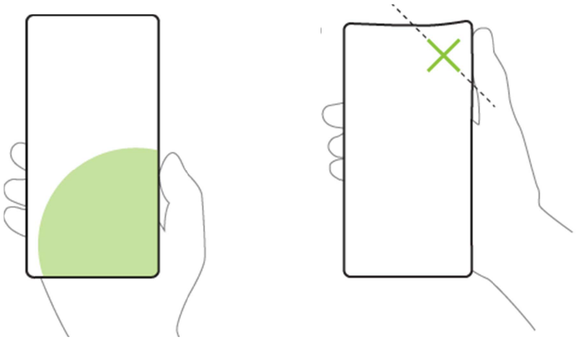

Figure 1. When used with one hand, current phones have a limited functional interaction zone (in green, on left). We explore bending the device to augment one-handed, open-air interactions (right).

Several usability issues occur with one-handed touch interactions, the main ones being the presence of unreachable touch targets, thumb screen occlusion, and constant change of grip, which sometimes lead to the need to use two hands, or to drop the phone [3]. While researchers have proposed new interaction to maximize thumb input [9,12,19,29], or the use of alternate sensors for input [18,21,22,27], the problem of one-handed interactions remains.

Deformable devices offer an opportunity to address some of these issues. Flexible displays promotes mobility [26], which leverages the comfortable use of smartphones in mobile environment. The deformability of flexible displays offers novel interaction techniques, such as bending a corner up or down which has been shown to be a feasible and effective input method for flexible handheld devices [10,13,16,20,24,25]. They can be particularly suited for continuous bipolar, as well as quick response actions [1].

In this paper, we explore the potential of deformable devices to address one-handed interaction issues with smartphones. We first set out to determine the use of common single-hand mobile interactions through an online survey. Then, we designed and evaluated one-handed deformable gestures that offer the potential for addressing the finger reach limitation on large smartphones. We identify the fastest and preferred gestures to propose the best gestures for single or repeated rapid actions, and discuss their impact on typical one-handed interactions problems.

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RELATED WORK

To study one-handed deformable gestures for flexible smartphones, we explored two groups of prior research: deformable interactions on flexible devices, and one-handed interactions on rigid smartphones.

Deformable Interactions on Flexible Devices

Early works [2,20] explored the conceptual idea of bendable interactions and successfully proved these interactions to be viable. In most recent years, deformable interaction research has broadened across various areas, such as interaction techniques [7,16,23], applications [10,13,15,28] and the physical characteristics of flexible devices [6,11,14].

PaperPhone [13] was the first prototype to use an actual flexible electrophoretic E Ink display. Lahey et al. studied the use of bend gestures with common smartphone interactions such as navigating a contact list or browsing through a music player. The participants held the flexible prototype with their left hand, and used their right to interact with the right half of the prototype. The authors found that users preferred bend gestures that were conceptually simple and less physically demanding.

Kildal et al. [10] presented the first fully flexible prototype with the Kinetic device. They implemented two main interactions, bending and twisting the whole device, both performed by holding the landscape device with both hands. They propose a set of initial design guidelines, including that bend and twist deformations are more easily performed using two hands, especially for larger devices.

We found two prior works that proposed interactions that can be performed with a single hand. Gallant et al. [7] presented interaction techniques for foldable user interfaces. Among the techniques, two can be performed using only one hand: the scoop technique, which consists of holding the device on the bottom side and creating a crease with the thumb, and the squeeze technique, done by holding both sides of the device with one hand, and creating a concave or convex shape. Unfortunately, they do not propose any evaluation of those techniques. FlexView [5] examined z-axis navigation on a touch-enabled flexible mobile device. Their interaction language consisted of leafing and squeezing the device as well as using touch, the latter being performed using a single hand. The results showed squeezing to be faster than touch input in the pan-and-zoom task.

More recently, Ahmaniemi et al. [1] tried to answer the question “What is a device bend gesture really good for?”. They evaluated gestures and use-case pairing for a landscape flexible device similar to the Kinetic. Their initial study identified the actions of zooming and list browsing to be best performed with device-deformation gestures, as opposed to map navigation, web browsing and horizontal sliders. They found that bend gestures are optimal for continuous bipolar parameters and when quick reactions are required, such as calendar alarms, calls, switching the device on/off, or switching applications on/off.

These prior works introduced deformable one- and two-handed gesture patterns, and evaluated them for a variety of tasks. However, little work exists in examining the details of one-handed usage of flexible handheld devices.

One-Handed Interactions on Rigid Devices

Due to the increase in device size of current smartphones, touch input often requires bimanual operation, one hand to hold the device and the other to perform gestures [13]. However, in many mobile environments, one-handed input is desired but often difficult to achieve given the ergonomics of unimanual operations [3,4,9,12,29]. Because of the limited reach of the thumb when the device is held with one hand, common problems with one-handed touch input on smartphones include unreachable targets and screen occlusion caused by the thumb, resulting in limited input capabilities with one hand without re-gripping. In response, researchers have proposed various strategies to address these problems such as maximizing thumb input, using pressure as an input or other sensors for interaction.

While there are a number of ways to hold a mobile device with one hand, the most practical one that limits usability issues is to place it in the palm of the hand with fingers on the sides, as illustrated in Figure 1 on the left [3]. To extend thumb interaction while using this grip, researchers have looked at how to maximize the use of the thumb input. Yu et al. [29] propose BezelSpace and CornerSpace, a tailored user interface for thumb interaction designed to access difficult targets. In the first design, the user swipes from the bezel without lifting the thumb and activates an extended cursor. The user then can manipulate the cursor to unreachable targets from within the thumb’s reachable area. The second design involves swiping from the bezel and lifting the thumb. Once lifted, a four-way navigation button appears at that location, which allows users to select the four corners. Boring et al. [4] present Fat Thumb, which uses the thumb’s contact size as a form of simulated pressure and integrate it as a means to pan and zoom. This interaction replaces the pinch gesture, which is difficult to execute with one hand.

Aside from touch input, the use of pressure sensors is also commonly found in prior works. GraspZoom [18] placed a force sensitive resistor on the back of the device to detect the pressure applied by touch input on the front. They apply this scheme to zooming and scrolling. Spelmezan et al. [22] placed pressure sensors on both sides of their SidePress prototype and offered it as an alternative input method to scrollbars, drag-and-flick or pinch-to-zoom. Their results suggest that users can precisely and efficiently control SidePress, and it is more efficient than the drag-and-flick gesture when scrolling large documents. Brewster et al. [27] conducted initial exploration in using the pressure inputs with the fingers on the sides of a device.

In addition to these methods, other interesting strategies include using different sensors and altering the physical movement of the device for interaction. Spelmezan et al.

[21] designed a power-up button on the smartphone. It is a physical button placed on the upper left side of the device and can detect pressure as well as proximity. This enables gesture interaction with one thumb without interacting with the touch display. In parallel, Holman et al. [8] also proposed measuring the pressure on the side of the phone to detect finger position.

These prior works suggest a clear call to order to investigate strategies to enable one-handed interactions in handheld devices. In this paper, we extend beyond current rigid devices and explore the possibilities of flexible devices using deformable interactions.

SURVEY ON ONE-HANDED USAGE PATTERNS

We conducted an online survey to investigate one-handed usage patterns on smartphones. Our goal was to identify user's preferred handedness for one-handed tasks in smartphones, where they find themselves most often having to perform one-handed tasks (e.g. walking, sitting), and which tasks are typically performed with a single hand. With this survey, we aimed to make an informed decision about our users for the experiment to follow.

Our survey was administered online during a 2 week period. We used social media to find participants. We drew two $10 gift cards among the participants.

Participants

158 participants (65 females) completed our questionnaire, with an average age of 26 years fold (18-61 range). Most participants reported being right handed (87.34%), while the rest was split between left handed (6.96%) or ambidextrous (5.70%).

The top 10 phone models possessed by participants were the Samsung Galaxy S2 and S3, the iPhones 4, 4S, 5 and 5S, the Google Nexus 4 and 5, the HTC One and the Blackberry Bold. The two most popular models are the iPhone 4S (12.67%) and the Galaxy S3 (11.39%).

Types of One-handed Interactions

The majority of participants (72.15%) preferred to use their right hand when performing one-handed tasks on their phones. The rest were divided between using their left hand (8.86%), using either hand with no preference (8.23%), or using both hands equally (10.76%). When reclassified using handedness, these values hold true: 70.89% of participants preferred using their dominant hand for one-handed interactions, with 10.13% using their non-dominant hand.

Many participants explained that they adapted their device usage to the phone's UI. One participant found that "most UI for applications cater to the thumb being on the right side of the screen". Another participant (left handed, but uses their right hand for one-handed tasks) claims that "software is designed for right handed people". Participants also mentioned the placement of icons and buttons on a device, which guide a user to operate their phone with a certain hand (typically the right). Finally, a right handed participant mentioned choosing to use his left hand to operate their phone to leave their dominant hand free for other things if need be.

Locations of One-handed Interactions

Our survey results also show that the participants use their smartphones with one hand in a variety of scenarios: 48.10% of participants use them while walking, 43.04% while standing, 32.38% while sitting, 24.68% while resting the smartphone on a surface (both arms on a table), and 31.65% without any preference.

Of the 105 participants that provided an explanation for where they use one handed interactions, 8.57% claim to primarily use their phones with one hand and will only use two when necessary. For users who prefer to only use one hand, some claimed that "two hands has too much screen occlusion", it is "not comfortable", and that "the actions required to operate the phone usually requires only one hand." Other users resort to using their phones with one hand when they are multitasking and using the other for something else, with one user specifying that they "only use two hands if [they] need stability or for certain gestures such as pinching" or "to type". 11.43% of participants will use one hand as a precautionary measure. Interestingly, two third of these users will not use their devices with one hand as they fear dropping their phones, while the other third will use their devices with one hand for their own safety – in case they trip, for example. One participant who uses her phone with one hand while walking says she "can concentrate on maintaining [her] balance with the other hand whilst walking", another said if she "falls, trips or slides on ice, [she] wants to be able to break [her] fall".

On the contrary, 7.62% of users explicitly expressed primarily using two hands when operating their phones and will only use one when necessary, such as for "notification checking". Some participants said they use two hands because of the large size of their devices. One user claimed they "rarely use [their] phone in one hand since it's usually too large to perform tasks and [they] need both hands; one to hold [their] phone and the other to perform a task".

Tasks for One-handed Interactions

Finally, we inquired about common high level one-handed tasks in smartphones. The tasks most commonly performed with one hand are those which involve a single tap or a short swipe on the screen: the most popular tasks are unlocking the phone (81.65%), selecting an app (77.85%), scrolling through websites (75.95%), and viewing pictures (73.42%). Other common tasks include using the dial pad (60.76%) and finding a contact name (62.03%).

There is a drop in the proportion of users who perform tasks one handed when the task requires a variety of rapid gestures, or gestures requiring more than one finger. Participants do not report often texting with one hand (34.18%), likely attributed to the lack of speed. Zooming on a map is not popular with one hand (17.09%), since two fingers are

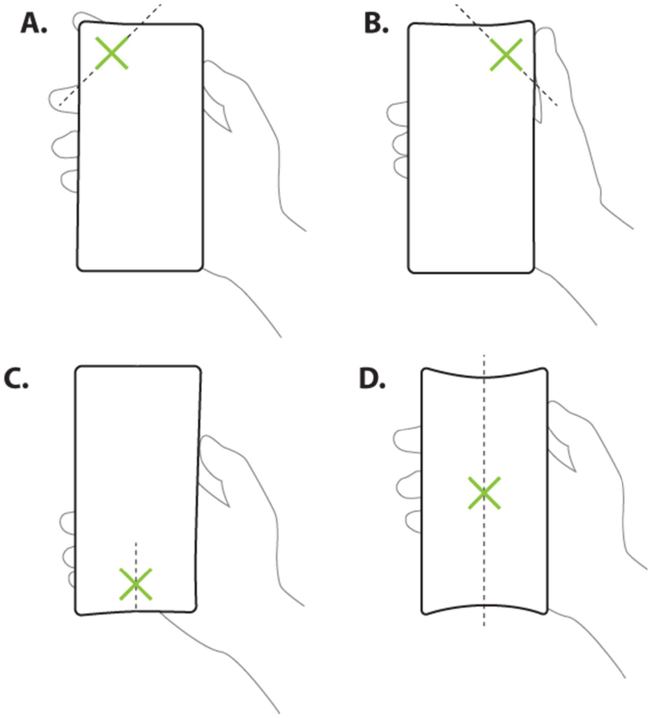

Figure 2. One-handed deformable gestures locations, with the right hand, performed up: A) top left corner, B) top right corner, C) lower bottom, and D) center.

required to perform a pinching gesture, which is physically awkward to do using one hand while holding the device with that hand. Finally, the task of panning a map is only performed with one hand by 31.01% of users. While this might be surprising given its similarity to the gesture performed when scrolling through websites, its low use is probably due to the combination of map tasks, pan and zoom, for which the latter requires two fingers.

Limitations

The social networks of researchers who disseminated the survey invitation include contacts living outside of Canada, and we assume that a proportion of those participated. However, without geographical data from participants, we do not know the exact composition of the participants.

We also acknowledge that self-reported common tasks may not be an accurate reflection of actual tasks. Many common operations are sub-tasks, and users may not consciously notice them, which could affect their reporting. Still, we believe this has minimal impact, since our high level survey produced useful information that will influence our gesture and experiment designs.

Summary of Results

This survey provides us with background information on one-handed gestures, which we will use to guide the design of our one-handed bend gesture experiment.

The large majority of users use their right hand to hold and interact with their rigid smartphone with a single hand, indicating that our bend gestures must be able to be performed with the right hand. However, a quarter of participants used their left hand exclusively or interchangeably. This indicates that a non-negligible proportion of the population could still benefit from left-handed bend gestures.

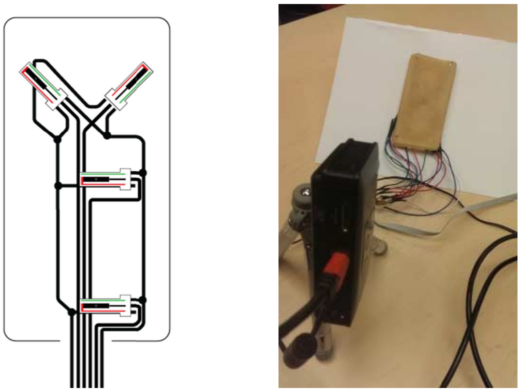

Figure 3: Our flexible circuit contains four bi-directional sensors (left), and the experimental setup (right).

One-handed usage of smartphones is more common in mobile scenarios (i.e., walking, standing) than in relatively more stationary situations. The one-handed gestures are typically single, unique touch events, or identical events that are repeated quickly. This information will help us design and conduct our experiment.

ONE-HANDED DEFORMABLE GESTURES

Prior to the experiment, we gathered a small group of expert HCI researchers to generate a set of possible gestures given a flexible mockup prototype using one hand. Our mockup prototype was made of silicone, and approximated the size of current large smartphones. From all the collected gestures, we selected a subset to evaluate by considering ergonomic constrains, hand sizes and dexterity. For instance, gestures that were only possible for users with very large hands were discarded. We also selected single gestures, i.e. bending one part of the display at once, as complex, or multi gestures required too much dexterity for most users.

The selected gestures are performed in four locations (top-left corner, top-right corner, central bend along the vertical axis, and lower bottom bend along the vertical axis) and in both directions (up and down, which can be referred to as concave and convex, respectively) for a total of eight gestures (Figure 2). To keep a consistent mental model across location, the direction is based on the movement exhibited by the sides of the device. This classification by location and direction is based on the two most popular bend characteristics in prior work [13,24].

ONE-HANDED DEFORMABLE PROTOTYPE

We fabricated a flexible prototype using the dimensions of a representative popular phone, the Samsung Galaxy S3. Our prototype measured 4 mm x 70 mm x 136 mm. We constructed the prototype out of silicone, and augmented it with four Flexpoint 1” bidirectional bend sensors to detect the eight gestures (Figure 3). We connected the prototype to an Arduino microcontroller, and developed an application that recognizes our 8 pre-defined deformable gestures from the sensor's raw data and provides users with instructions and visual feedback about their interactions. We used a Pico projector to create an interactive display on the prototype.

We followed a similar process as the one outlined by Lo and Girouard [17]. Prior the experiments, we tested mock prototypes made out of different material hardness and selected a flexibility that was most suitable for one-handed deformation. The resulting prototype is 60A shore hardness. A two-part mold was machined to cast the silicone mold. The flexible circuit was placed in the middle of the molds and silicone was cast on both sides. This process created a uniform, comfortable prototype.

EXPERIMENT FOR ONE-HANDED BEND GESTURES

We designed a study to investigate the performance of the 8 one-handed deformable gestures. Specifically, we were interested in learning about how gestures are performed with each hand, which gestures are faster, and which are more comfortable, and finally whether the gestures are appropriate in varying scenarios. We evaluated the effect of handedness on the gestures, as both hands are used for one-handed mobile use by a significant proportion of the population, as shown in the survey.

We chose to mimic mobile scenarios preferred by users for one-handed interactions. Participants were in sitting condition to minimize overall fatigue, but they were required to hold the flexible smartphone prototype in the air while performing the gestures, without their arms or elbows resting on the table.

Task

We developed two tasks for participants: the single event task, and the repeated event task. Figure 4 illustrates the visual feedback provided for each event.

The **single event** is designed to determine which gestures are the quickest to perform. These gestures would be useful for short interactions, such as notification dismissal, selection, answering a phone call. To accomplish a single event task, participants performed the correct bend gesture once.

The **repeated event** illustrates scenarios where one handed gestures are repeated a number of times, such as when browsing photos, navigating a music library, or scrolling a webpage. In the repeated event task, participants were required to perform the correct bend gesture repeatedly nine times. Participants received a visual feedback for each successful repetition.

Study Design

To evaluate the gestures, we designed 2x2x4x2 factorial repeated measures within-subject design, with the factors: *hand* (left, right), *task* (single event, repeated event), *gesture location* (top-left corner, top-right corner, central squeeze, and bottom squeeze) and *gesture direction* (up, down). We conducted three trials for each condition in the single event. We counterbalanced by hand and task, and randomized by gesture.

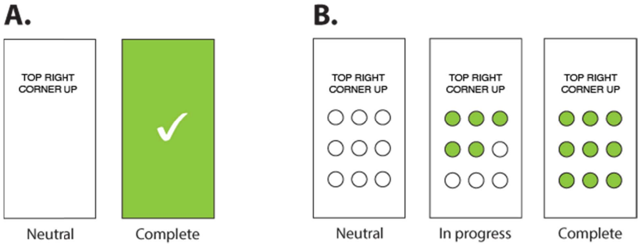

Figure 4. Visual feedback for single event task (A), and repeated event task (B)

We measured the duration of each gesture and the number of errors. The duration of a gesture is measured from the time the gesture name appears on the screen to the time the gesture is correctly performed and recognized by the system, which may include time to change grip. Participants rated their level of preference ("I like performing this gesture") and comfort ("I find this gesture comfortable to perform") on a 5-point Likert scale, where 1 is strongly disagree and 5 is strongly agree.

The experiment started with a training period, where participants could practice every gesture. They received a simple feedback that indicated which gesture was activated: e.g., the top left corner turned blue when the top left gesture was performed up, and it turned orange when it was performed down. Participants told the experimenter when they were comfortable with the gestures and were ready to proceed.

Participants

18 participants (10 males) completed our study (mean age of 28.8 years old). Two had previously participated in a flexible display study. 15 participants were right handed, and an equal number (though a different subset) reported using their right hand when handling their mobile device one-handed. This followed the same proportion of users found in the survey. Participants were given a $10 gift card as compensation.

Results

Single Event

We aggregated the results of the three trials and we ran a 3-way within-subject repeated measured ANOVA using the factors *hand*, *gesture location*, and *gesture direction* on the duration and error.

We found a significant effect of gesture location ($F_{3,51} = 9.33$, $p < 0.001$, $\eta^2 = 0.35$) and gesture direction ($F_{1,17} = 18.39$, $p < 0.001$, $\eta^2 = 0.52$) on duration. Pair-wise post-hoc comparisons found the central squeeze to be significantly faster than all other gesture locations (center: M = 4425.58 ms; top right: M = 5600.03 ms; top left: M = 5857.37 ms; bottom: M = 6325.51 ms). Gestures up were significantly faster (M = 4958.02 ms) than gestures down (M = 6146.02 ms). All pair-wise comparisons performed are Bonferroni corrected ($p < 0.05$).

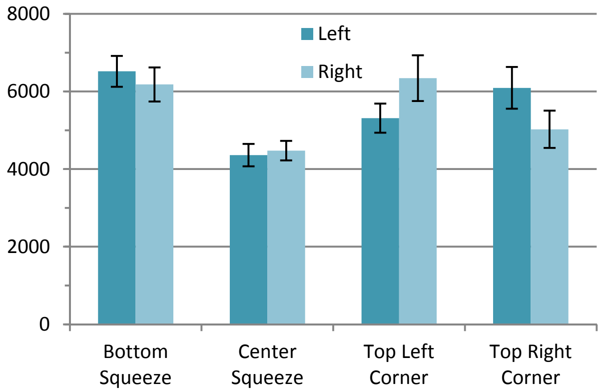

Figure 5. Duration (in ms) for the 4 locations by hand, for the single event task. Error bars show standard error.

We also observe a significant interaction of hand and gesture location on duration ($F_{3,51} = 3.30$, $p = 0.046$, $\eta^2 = 0.16$), as illustrated in Figure 5. Pair-wise post-hoc comparisons identified that in the left hand, the central squeeze location is significantly different from the bottom squeeze location as well as from the top right location. In the right hand, the central squeeze location is significantly different from the bottom squeeze and the top left location.

The interaction of location and direction on duration is also significant ($F_{3,51}=5.06$, $p = 0.006$, $\eta^2 = 0.23$). Figure 6 displays the duration this interaction. Pair-wise post-hoc comparisons found that the bottom location and the top right location are significantly different between directions.

Finally, we found 3-way significant interaction of hand, location and direction on number of errors ($F_{3,51}=4.40$, $p = 0.010$, $\eta^2 = 0.04$). The top-right down gesture with the left hand obtained the highest number of error (M = 0.99, SD = 0.30), followed by the top-left down gesture with the right hand (M = 0.70, SD = 0.21). This is the only significant factor or interaction with the number of errors.

For every error that occurred, the system recorded the gesture that was wrongfully produced. Table 1 displays the number of each type of wrong gesture produced for every gesture asked. The table does not differentiate between the type of error, mainly between participants who made a mistake and choose to produce the wrong gesture (participant error), and between situations where the wrong sensor is activated because the gesture was not performed correctly (prototype error). However, given that our sensors only produce a single value, which we use to determine their direction, any error in direction only must be participant error. An example of this situation occurs, if the gesture asked is a top left corner down and the recorded gesture is a top left gesture up (12 errors total of this nature in Table 1).

Table 1. Average number of errors by location and direction. Cell shading indicates importance.

			Gestures recorded							
			Top Left Corner		Top Right Corner		Center Squeeze		Bottom Squeeze	
			D	U	D	U	D	U	D	U
Gestures asked	Top Left Corner	D	0.00	0.11	0.10	0.01	0.17	0.12	0.02	0.00
		U	0.03	0.00	0.01	0.11	0.01	0.14	0.00	0.10
	Top Right Corner	D	0.00	0.04	0.00	0.04	0.43	0.09	0.00	0.01
		U	0.00	0.07	0.00	0.00	0.00	0.25	0.00	0.00
	Center Squeeze	D	0.01	0.00	0.04	0.00	0.00	0.02	0.07	0.03
		U	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.30
	Bottom Squeeze	D	0.00	0.01	0.00	0.00	0.16	0.01	0.00	0.27
		U	0.00	0.00	0.00	0.00	0.03	0.07	0.07	0.00

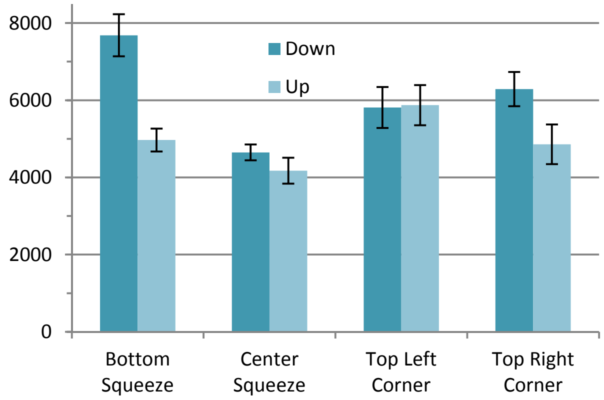

Figure 6. Duration (in ms) for the 4 location, by direction, for the single event task. Error bars show standard error.

Repeated Event

In analysing the gestures from the repeated event, we noticed that the first repetition of this event followed closely the values of the gestures in the single event, but that repetitions 2 to 9 did not: the single event gestures averaged 6285.47 ms on the first trial, and the repeated event gestures averaged 6696.51 ms on the first repetition, while the other 8 reps averaged 1789.49 ms. This result is reasonable, since the first repetition is essentially the same task as the single event task. Given this pattern, we chose to only analyse repetitions 2 to 9.

We aggregated the results of the 8 repetitions, and ran a 3-way within-subject repeated measured ANOVA using the factors *hand*, *gesture location*, and *gesture direction* on the duration and number of errors. We found no significant factor or interaction in this analysis, indicating that the variables hand, gesture location nor gesture direction contributed to the variability in the duration or the number of errors.

Questionnaires

We performed Friedman tests on the questionnaire data with the factors *task*, *hand*, *gesture location* and *gesture direction*. For the preference question, we found significance for the factors event ($\chi^2 = 14.67$, $p < 0.001$), location ($\chi^2 = 62.53$, $p < 0.001$), and direction ($\chi^2 = 158.06$, $p < 0.001$). The repeated event yielded stronger agreement (M = 3.29, SD = 1.25) than the single event (M = 3.15, SD = 1.33). The bottom location had the lowest preference (M =

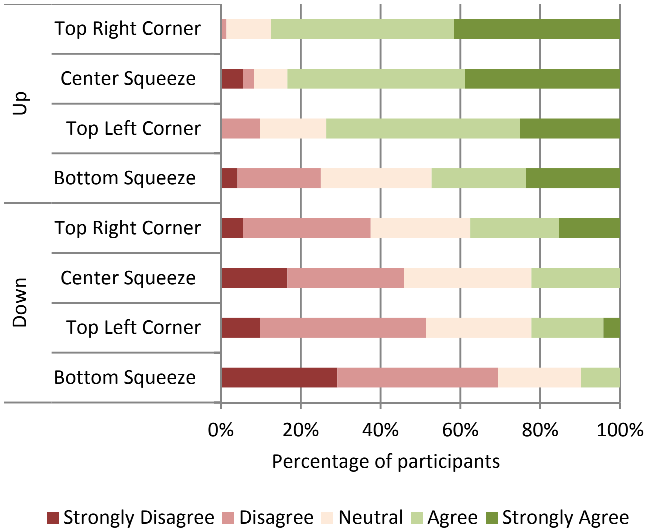

Figure 7. Distribution of Likert scale responses for the question on physical comfort "I find this gesture comfortable to perform", ordered by the level of agreement.

2.70, SD = 1.33), followed by the top left (M = 3.24, SD = 1.21), the central (M = 3.37, SD = 1.31) and the top right location (M = 3.57, SD = 1.18). Finally, the up direction obtained stronger agreement (M = 3.83, SD = 1.10) than the down direction (M = 2.60, SD = 1.19).

The results are almost identical for the physical comfort question, with the factors location ($\chi^2 = 65.63$, $p < 0.001$) and direction ($\chi^2 = 172.27$, $p < 0.001$) being significant. The bottom location is least comfortable (M = 2.76, SD = 1.26), followed by the top left (M = 3.27, SD = 1.14), the center (M = 3.34, SD = 1.27) and the top right location (M = 3.69, SD = 1.13). The up direction is also more comfortable (M = 3.92, SD = 1.02) than the down direction (M = 2.61, SD = 1.10). Figure 7 shows the distribution of the responses for the physical comfort question, which is representative of the data of both questions.

Observations

Throughout the experiment, we observed the interactions the participants had with the prototype and the gestures. Figure 8 illustrates some of the grips and gestures that participants performed.

While users had no trouble differentiating the corner gestures from each other (though some confused left and right on occasion) and from the center and bottom squeezes, participants seemed to have trouble separating the center and bottom squeezes from each other, occasionally persisting in spite of feedback indicating an error. In addition, these interactions sometimes resulted in a false activation of another (wrong) sensor. For instance, very large bottom bends sometimes resulted in activations of the center sensor.

The directionality of the gestures (up/down) can be problematic for device-spanning interactions (center and bottom gestures), depending on whether the participant perceived the up gesture as moving the center or the sides of the prototype towards them. Some users understood pushing the sides of the device upwards to constitute up (creating a concave shape), and moving the sides in the opposite direction to mean down (convex shape), while others used the center of the device as their reference point, effectively reversing the interaction in their mental model. Feedback from the device allowed users to correct erroneous gestures, but they re-occurred frequently. Participants seemed evenly split on whether they found our assignment to align with their understanding of the device. Our directionality labelling was based on prior work [1,13], but we do acknowledge that it may be somewhat arbitrary.

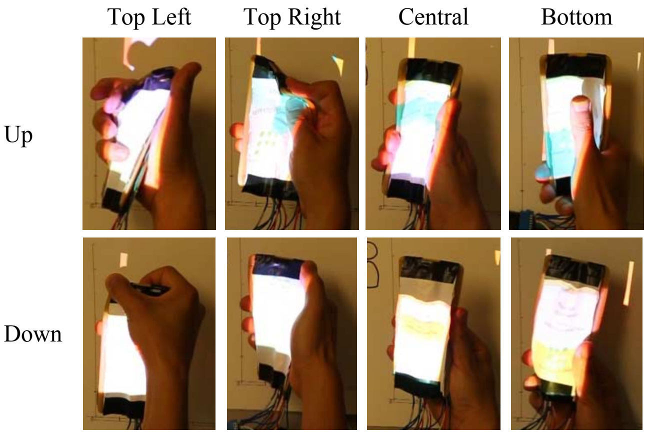

Figure 8. Examples of the gestures performed by our participants.

The degree of fine motor control possible when interacting with the device with one hand also influenced the variety of possible interactions. Many participants had difficulty activating the corner opposite their thumb (e.g. the right corner while holding with the left hand) and were forced to change their grip to interact with this corner, only to return to their original grip afterwards.

Users exhibited a variety of grips when trying to interact with certain gestures: some occluded the screen significantly (e.g. the top left down gesture in Figure 8), some resulting in an unstable hold during the change of grip; some users dropped the device or some activated different sensors. Many users voiced displeasure and frustration with having to change grip, and voiced a preference for maintaining the same grip for all interactions. We observed that many users adapted to re-gripping by bracing the prototype against the desk to stabilize the prototype during re-gripping - an option that would not always be available in practical applications.

Hand size influenced how the device was gripped, and the ability to reach corners (very small hands) or to control how they bent corners (very large hands). Users with large hands were able to adopt a pinching grip - activating the device using their index finger and thumb instead of using their whole hand. Almost all participants used their pointer finger to put pressure on the back of the device to achieve a squeeze in the downward direction. To achieve the bottom squeeze gestures, almost all users had to change their grip on the device, moving their hand downwards on the device. They then changed their grip again to perform the following gesture (unless it was a bottom squeeze gesture again).

DISCUSSION

Our investigation with the one-handed deformable prototype produced useful insight about how participants performed various gestures. We found the central squeeze gesture to be the fastest of the four locations in the single event task. It is also one of the two preferred gesture. It is easy to perform, and does not require a really specific grip, which means it can be done quickly in a variety of hold scenarios. It gathered a high level of agreement for comfort. We recommend to associate quick and important actions with this central gesture.

Second in speed are the two top locations. It is important to note that the two top location gestures are performed differently by each hand: with the left hand, the top-left gesture is done using the thumb finger, but it is done using the index finger when performed with the right hand. In our analysis, we kept the grouping by location, and not by which finger performed the gesture, so the interface would be consistent no matter which hand is used, similarly to current touch interfaces. For instance, dismissing a notification would be done using a top right corner bend up, no matter whether it would be performed using the left or right hand. Yet, our post-hoc analysis revealed a difference in performance through the interaction of hand and location. For the top locations, the gesture performed with the thumb (illustrated in Figure 2B) is faster than the one performed with the index (Figure 2A). This result is also consistent with the questionnaire data as well as our observations. Given that most users are likely to use their right hand to perform the one-handed gesture based on our survey results, we recommend placing important actions in the top right location, as they could be accomplished in a similar speed range as with the central squeeze.

The interaction of hand and gesture location leads us to wonder about whether we should create interfaces that keep constant the set of actions, or the gestures performed. We can easily imagine a smartphone that could detect the hand that is holding it, and adjusts the expected gesture accordingly. It would bank on muscle memory transferability among hands, yet might confuse the user by lack of coherence. A follow up study would clarify this.

In general, the bottom gestures did not obtain particularly high notes from the preference data, mainly due to the fact that participants had to change their grip to accomplish this gesture. We also notice that a large number of errors with the squeezing gestures come from them being mistaken: a bottom gesture recognized as a central gesture (28 errors), and central gesture being recognized as a bottom gesture (41 errors). We have confidence that the inability for users to differentiate the squeezes relates more to their inability to deform the device correctly with one hand than to a sensor issue. We noticed that it is difficult for users to perform a bottom squeeze without also squeezing the center of the device. Given that the bottom squeeze was fast in the down direction, we propose two solutions. An improved sensor placement and recognition algorithm may better recognize the two gestures distinctively, eliminating some error cases. Alternatively, we suggest the merge of the two gestures: a bottom or a central squeeze would produce the same result in the latter solution.

The duration data and the questionnaires point to the fact that up gestures are superior to down gestures: they are faster, and they are more liked. This result is consistent with prior work [13,24]. In this case, it is due to the fact that the hand is placed behind the device, so the user has to simply push to activate. Upwards gestures required less re-gripping, which is preferred by users. Re-gripping requires a higher focus of attention, and sometimes a second hand, both of which lead to a higher cost of execution [3].

An interesting result comes from the lack of significance for the factor hand in both the duration and questionnaire data. While this does not indicate a lack of difference between the hands, it does indicate that the two hands offer somewhat of an equivalent experience performing single handed bend gestures. This means that we can offer left handed interactions at almost no loss of performance, which might benefit a quarter of the user population, based on the number of participants who reported using the left hand, both or either hands to currently perform one handed interactions with their smartphone. This provides deformable devices a considerable advantage over rigid, touch-only devices.

The repeated event yielded no significant results. In this context, this indicates that once users position their hand correctly, they can perform any gesture repeatedly at approximately the same speed. This indicates that designers can use other criteria to select the gesture to be used to scroll a website or browse pictures, since individual gestures do not matter for speed. However, users performed repeated actions at a much faster pace than new actions (3.6 times faster). This suggests that designers should keep the same gesture for subsequent actions of the same nature, whether it being associated to the same action (changing page on an eBook reader), or with different actions that should be performed consecutively (opening the camera application and taking a picture).

Occlusion is an important issue with thumb interaction, as the thumb can restricts the user from viewing the screen, missing specific targets or important information. While we can notice occlusion in the top-left gesture in Figure 8, this mostly occurred with the top gesture location located under the index, for down gestures (the top-left down gesture with the right hand, and the top-right down gesture with the left hand). As these gestures did not obtained a stronger performance or preference from the participants, we do not believe occlusion to be a main issue with one-handed bend gestures as it can be for one-handed touch gestures. In addition, better, more sen-

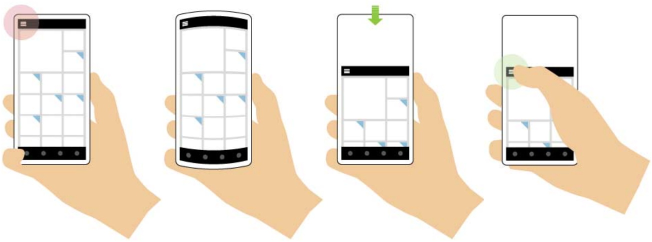

Figure 9. A squeeze gesture could pan down the entire GUI to access an area otherwise unreachable without re-gripping the device, in this case an element of the top menu bar.

sitive sensors and gesture recognition algorithms might alleviate this issue further.

Potential Application

To illustrate our results, we propose a potential application of the deformable gestures that will ease the shortcoming of reachability of current touch phones with our deformable gestures. We make use of the suggestion to merge the central and bottom squeeze gesture, and create a single squeeze gesture, with up and down directions.

This squeeze gesture up seem suited for triggering a down pan motion of the entire GUI so that all its top active elements are reachable without the need to overextend one's finger of change hand posture (Figure 9). When the user cannot reach a top left button with his finger in a one-handed situation, he could simply squeeze up the device to scroll the GUI down until he can reach it. He would then be able to interact with the GUI at the right height, and squeeze again to have the GUI automatically scroll back up. With this potential application, the user has now performed an interaction that is currently difficult to perform on current handheld devices without having to change his grip.

Limitations

We acknowledge the possibility that bends might mistrigger touch operations when offered conjointly. However, our goal with this work was not to integrate the two input modalities in a functional device, though this would be an interesting future work. Instead, we focused on simple and fast tasks such as unlocking or answering the phone, where typically there are no other commands available, so the chance of accidental touches is low. Also, while the presence of a touch screen might have changed users grip slightly, we believe that general positioning would be similar, so our results should hold.

Our experimental design had a higher ratio of top to bottom gesture, based on prior work [e.g. 13,24] as well as ergonomic constraints: it is simply hard to perform precise and different gestures on the bottom. However, our questionnaires asked about gestures individually, to minimize this experimental bias.

Among the limitations of our device, we have already pointed to the fact that some gestures generated a false positive when a very large bend was produced, such as a top right corner registering a central gesture. A better gesture recognition algorithm should take care of this issue. A confound to this finding was a warping of the prototype through the study, which potentially made bends in the down direction more difficult. The lack of interactive display on the prototype may have affected the experience. However, to minimize this issue, we did not project any information that required a detailed placement, everything was located on the center of the display. Finally, while we tried to produce a flexible printed circuit, it was not strong enough to withstand experimentation, and we create a prototype with wires. This may have influenced the gesture performance, but we expect that the effect would have been the same over every gesture.

CONCLUSION

This paper explored one-handed deformable interactions for flexible smartphones. First, we inquired about current one-handed interactions in rigid cellphones through an online survey. Most of our 158 participants used their cellphone one-handed using their right hand, in context of mobile scenarios, to do single, short tasks. We then identified 8 deformable gestures, based on four locations (top left corner, top right corner, squeezing the central location vertically, or squeezing the bottom location vertically), and two directions (up and down). Finally, we ran an experiment to evaluate those 8 gestures performed with each hand, in the context of single tasks and repeated tasks.

Our results show promise for one handed gestures, and warrant further exploration. The two best gestures were the top right up and the center squeeze up, which were faster, preferred, and more comfortable than the rest. We found no hand preference, which indicates that the gestures could be implemented to fit the needs of a wider range of the population, instead of favoring right-handers. We noticed that occlusion, one of touch's weaknesses, is not a problem for deformable gestures. While the experiment did not explicitly measure changes in hand posture and grips, we observed that almost all participants had to re-grip to perform certain gestures. Well-designed bend gestures would likely minimize the overall need for repositioning one's hand(s) on the device. Hence, we believe that one-handed deformable gestures are an interesting, complementary interaction to touch, as they can alleviate some of one-handed touch's issues.

In addition to exploring more complex gestures and improving on the gesture recognition algorithm, the main future work for one-handed bend gestures concerns the implementation of the gestures with real applications. For instance, it would be worth exploring them in the context of applications, such as answering a phone call, browsing an article, dismissing notifications. An insitu evaluation of the gestures would also provide important information concerning their use.

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