Feeling It: The Roles of Stiffness, Deformation Range and Feedback in the Control of Deformable UI

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ABSTRACT
There has been little discussion on how the materials used to create deformable devices, and the subsequent interactions, might influence user performance and preference. In this paper we evaluated how the stiffness and required deformation extent (bending up and down bimanually) of mobile phone-shaped deformable devices influenced how precisely participants were able to move to and maintain target extents of deformation (bend). Given the inherent haptic feedback available from deforming devices (over rigid devices), we also compared performance with, and without, external visual feedback. User perception and preference regarding the different devices were also elicited. Results show that, while device stiffness did not significantly affect task performance, user comfort and preferences were strongly in favour of softer materials (0.45 N·m/rad) and moderate amounts of deformation. Removing external visual feedback led to less precise user input, but inaccuracy remained low enough to suggest non-visual interaction with deformable devices is feasible.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Haptic I/O.*

General Terms
Design, Human Factors.

Keywords
Deformable UI, stiffness, deformation, visual feedback, kinaesthetic feedback.

1. INTRODUCTION
There has been considerable interest in developing flexible and deformable user interfaces over recent years: devices that can be bent/twisted [3, 5, 14, 20, 26, 28], compressed [17] and pressed [4, 11, 26]. However, devices that are too physically difficult or uncomfortable to flex/deform accurately are likely to produce undesirable and inaccurate interfaces. Kildal [12] has shown that increasing stiffness negatively influences preference and performance when bending and twisting a deformable device. However, it is unclear how the required extent of deformation, in isolation as well as in relation to different stiffness, may have an impact. Features such as stiffness, elasticity and deformation extent have a profound effect on our ability to tactually judge the physical characteristics of an object [1, 10, 22], suggesting that more rigid devices provide less haptic feedback concerning user input. Also, when required to apply precise amounts of force, accuracy varies depending on the target force and the way it is applied [8, 18]. In other words, bending harder devices, and having to bend them to a large extent, may result in inaccurate input. However, the effects that different physical characteristics might have on how precisely and comfortably users can deform/interact with flexible devices have not yet been considered. In this paper we focus specifically on device stiffness and the required extent of deformation to fulfill the interaction.

There has been a similar lack of research within psychophysical science on the influence of object deformation on human control of force. To our knowledge, psychophysics has focused solely on isometric force, where the manipulanda are effectively rigid. Within this research, it is apparent that providing the individual with external visual feedback concerning how much force is being applied is necessary for precise application of target forces [6, 7, 18]. While haptic feedback (both kinaesthetic and cutaneous feedback) is of some importance, it is less accurate on it's own [7, 9]. Conversely, when judging the compliance of an object, cutaneous feedback is both sufficient and necessary [1, 10, 22].

Therefore, in this paper we look to contribute to both fields of research by investigating the influences of material stiffness and the extent of device deformation on ability to precisely deform a flexible device. In order to test if the cutaneous and kinaesthetic feedback from deformation provides sufficient information for accurate input, we also compared performance when presented with and without visual feedback. We used three mobile phone-sized flexible devices, which varied only in their stiffness, and tasked users with applying and maintaining target levels of deformation, specifically bending the device up and down (applying torque) with both hands. We measured precision in maintaining target levels of deformation and gained subjective user reports on the comfort and ease of use of each device.

2. BACKGROUND
2.1 Flexible Devices
Researchers have demonstrated many different designs of partially or fully flexible devices, which can be bent, twisted or otherwise deformed due to the use of elastic or malleable materials. These manipulations then frequently recreate facsimile outcomes in digital content. Mimicking and digitizing paper-based interactions (such as folding, leafing, piling *etc.*) are most common, by using physical paper as an input method [3], or paper-like flexible sheets, which can provide facsimile digital input [15, 26]. Other flexible devices have used similar shapes but for different purposes. Gummi [20] provided bending movements to control zooming

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and level-transition of map and file browsing applications. PaperPhone [14] aimed to show how an entirely flexible mobile phone could be controlled by simply bending the corners, or side, of the device. While these two devices had built-in displays, Cobra [28] used a blank deformable sheet and shoulder-mounted projector for flexible mobile gaming, by bending the sides and corners of the sheet. Twend [5] allowed for similar bending gestures but had no associated display.

All of these examples required users to bend or flex a part of the given device, but the amounts of bend/flex that users are required to perform, in order to produce a recognized input, vary across devices and the materials used to make the devices are also rather different, leading to varying levels of stiffness. For a flexible device to be useable, it must be comfortable to deform, and easy to deform accurately. Lee *et al.* [15] found that users believed a more rigid plastic material would be less preferable for use as an input device, compared to more flexible paper and cloth. This study involved no actual interaction, however, Kildal found that the preferences hold when actively engaged in navigation tasks, specifically using discrete and continuous bend and twist gestures [12]. Gallant *et al.* [3] used highly flexible paper; Twend [5] did not report the limits of available flex, but used foam and thin plastic. PaperPhone [14] used thin plastic and flexible e-ink display. In contrast Wightman *et al.* [26], Tajika *et al*. [24] and Gummi [20] used seemingly stiffer plastic devices, with Gummi in particular requiring relatively high maximum force (100N).

Most of these studies included only perfunctory user testing, and Wightman *et al.* [26] and Kildal [12] are the only examples to test the influence of device flexibility. Kildal found that the stiffest device resulted in the poorest task performance and the lowest user preference. Extent of deformation is also an important variable, one that has not been considered in previous studies. A controlled study that investigates both variables together is necessary to understand the role of stiffness and deformation in performance and preference in controlled input tasks, where accuracy of input is important. Stiffer devices will require more force to produce a given amount of deformation, and requiring more force can be less comfortable and more difficult to do accurately. We hypothesised that stiffer devices, and having to deform a device by a greater extent, will result in less precise deformation, due to being more physically difficult to bend. So we sought to answer the following research questions (RQ):

RQ1: Does device stiffness influence our ability to accurately deform a device?

RQ2: Does the extent of physical deformation influence our ability to accurately deform a device?

RQ3: How do device stiffness and deformation extent influence ease, comfort and enjoyment of use?

2.2 Force Control & Active Touch

Cutaneous tactile feedback from the fingers, particularly the size and rate of contact-area spread, resulting from investigative touching of objects, provides sufficient information for an individual to judge the comparative compliance of an object relative to another [1, 10, 22]. However this is true only if the object surface is at least partly compliant. Otherwise, if the surface is rigid (even if the object itself is compliant) a combination of both cutaneous and kinaesthetic feedback (from the muscles) is required in order to judge the compliance/hardness of an object [9, 22].

While haptic (cutaneous and kinaesthetic) feedback is sufficient to judge object material properties, it is largely insufficient with regards to precisely judging the degree of force being exerted to a rigid device or manipulandum. Removing cutaneous cues degrades accuracy of applied force, which suggests cutaneous feedback is of some importance [9]. However there are marked differences in precision of applied force when comparing cutaneous/kinaesthetic feedback alone to when also presented with external visual feedback [6, 7, 18]. This suggests that, when applying force to a rigid object, we need extra feedback concerning how much force we are applying in order to do so accurately. In fact, when presented with visual feedback we may even become dependent on it, as when presented with contradictory visual and haptic feedback (concerning the stiffness of a spring) responses were biased towards the content of the visual feedback [21]. When relying only on haptic feedback we regularly over-exert (i.e. overshoot) low target forces and under-exert (undershoot) high target forces, with better accuracy at moderate forces [7-9, 18]. What constitutes "low", "moderate" or "high" forces depends on the muscles being used (e.g. pressing with finger, squeezing with hand, pushing with elbow) and the individual's ability.

This dependence on visual feedback has also been shown within HCI interfaces based on isometric force input. Reducing or outright removing visual feedback results in much lower precision of targeting interactions, across a range of devices [16, 19, 23]. Audio feedback can successfully substitute for visual feedback [27], but some external feedback remains necessary. This leads us to the final research question we sought to address:

RQ4: Is haptic feedback from device deformation sufficient to accurately maintain force output or is external feedback necessary?

2.3 Kinetic Deformable Device

Kildal [13] has described the Kinetic Deformable UI Research Prototype (DUI-RP) device (see Figure 1, left), which served as a research platform for the Nokia Kinetic Device[1] (Figure 1, right). It consists of two rigid plastic grips at either end of a central flexible/deformable body, forming a shape similar to that of a smartphone. The device is elastic and so returns to it's original, flat, shape after being deformed. A set of strain gauges within the central body can detect bending and twisting gestures, with 10 bit resolution at 200Hz sample rate. Sensor values were taken over HDMI to a custom microcontroller, which filtered and amplified the values before sending them to the host PC over USB. For the purposes of the current study we limited interaction to only bending up and down (see Figure 2). Input from the device is based on deformation of the central body, and so the interaction language was chosen based on changes in the central body. Therefore pushing the central body up (pointing the ends down) constituted bending up and pushing the central body down (pointing the ends up) constituted bending down.

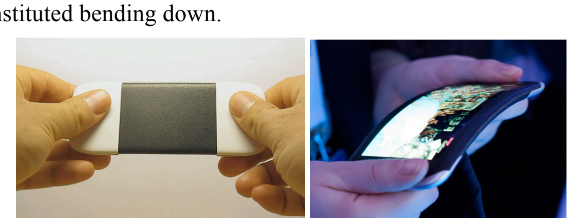

Figure 1: Kinetic DUI-RP (left) and Nokia Kinetic (right).

We used three DUI-RP devices, each aesthetically identical (as in Figure 1, left), but differing in the stiffness of the central body. The three devices, referred to here as *Soft*, *Medium* and *Hard*, had rotational stiffness of 0.45, 1.3 and 2.5 N·m/rad respectively. This

[1] http://research.nokia.com/news/12110

set of devices is equivalent to that used in Kildal [12]. As an illustrative example of the comparative stiffness, bending the *Soft* device might be like bending the sole of a beach flip-flop/sandal with the hands while the *Hard* device might be like bending the sole of a hiking boot.

3. EVALUATION

Lee *et al.* [15] identified bending as a common user-generated gesture for flexible devices, which had a high preference rating, suggesting it is a natural means of interacting with a flexible object. Bending is also a commonly used gesture in other deformable devices [5, 14, 20, 26, 28]. Therefore we also used bending as the primary interaction in our research, specifically one-dimensional, bi-directional bending. As mentioned before, participants held the DUI-RP devices at either end with both hands. Because both bending up and bending down were included in the task, we considered the neutral (flat) resting state as the starting position, with the target torque or deformation extents measured from here, both up and down.

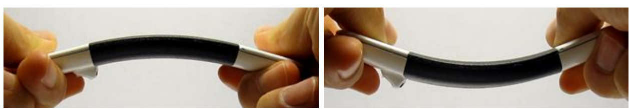

Figure 2: Bend Up Gesture (left) and Bend Down (right)

3.1 Task

A linear targeting/force-matching task was chosen as the means to evaluate the effect of stiffness, deformation extent and feedback on the precision of device deformation. This is a common task in other HCI research [16, 19] and is also very similar to force-matching tasks used in psychophysical science [6, 7, 18]. The task gives an indication as to how precisely users can apply and maintain target levels of force, by measuring the difference between the applied force and the target force (i.e. the error). Here we are applying the same process, only to levels of applied torque, or, more specifically, the extents of deformation resulting from applied torque. In our task we asked participants to maintain the target level of bend for a total of 8 seconds: 4 with visual feedback concerning the extent of bend and 4 without.

3.1.1 Feedback

The visual feedback for the task can be seen in Figure 3. In the middle of the screen is a rectangular ‘parking’ area indicating the neutral starting position of the device. The lines running vertically above and below parking indicate the size of the interaction space, extending from -10 to +10 in arbitrary distance units. The target bend distance to be acquired and maintained is shown as a short, horizontal line bisecting the vertical line. Bending-up targets were shown above parking and bending-down targets were shown below parking. The current extent of bend was indicated by the position of a circular cursor, which ran along the vertical line.

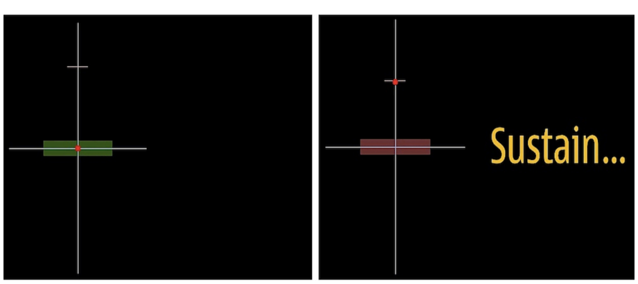

Figure 3: Task interface including cursor dot, central 'parking' area and target distance (short bisecting horizontal line).

Once the device had been bent sufficiently to bring the cursor in proximity of the target (within a distance of 0.49 of the target distance, i.e. 4.9% of the interaction space), the ‘sustain’ phase began. The sustain phase was split into two 4-second sub-phases: the first *with* visual feedback concerning user input and the second *without* visual feedback. During the first 4 seconds, the screen displayed the word “Sustain”, as shown in Figure 3, and the *cursor remained visible*, showing the current user input. After these 4 seconds, *the cursor was made invisible* and only the word “Sustain” remained onscreen for a further 4 seconds, instructing participants to maintain bend without the cursor, until the trial ended and the participant was instructed to return to parking.

3.1.2 Mechanics of Interface Deformation

Most of the research from HCI and psychophysics concerning force input has studied linear forces (measured in Newtons in SI). Examples of this type of input include pressing or squeezing. Bending a device with two hands, however, requires that a torque or momentum (M), and not a linear force, be applied with each hand. The SI unit for a torque is Newton meters (N·m). Thus, when applying a torque in opposite direction on each end of the device, the effect obtained is that one end of the device rotates with respect to the other end. In the case of a Kinetic DUI-RP, the rigid sections on each end, which are parallel to each other in the resting position, will rotate with respect to each other an angle α after the torque is applied (Figure 2). The ratio between the torque applied (M) and the resulting deformation angle (α) is called rotational stiffness (k), which depends on the physical characteristics of the deformable body. This relationship is described by the equation:

$$\frac{M}{\alpha} = k \qquad (1)$$

This is the rotational equivalent of Hooke’s Law. To investigate the effect of varying device stiffness (k) on the interaction, we kept either torque (M) or deformation angle (α) constant, and observed how the other variable was affected. Thus, we chose to run two separate studies: one where levels of torque were kept constant across devices with different k (Study 1) and one where angles of deformation were kept constant across devices (Study 2). Given the relationship shown in equation 1, each target distance in study 1 was reached by applying the same torque on each device, which resulted in different deformation extents. Conversely, in study 2, each target distance was reached by producing the same deformation angle on different devices, which required applying different levels of torque.

As mentioned, target distances through the interaction space ranged from 0 to 10 in both directions (bending up and down). 10 target distances were chosen, as other research on force-based input has found that users are able to apply this number of different force levels accurately [27]. The just noticeable difference (JND) of force production is approximately 10% [7-9, 18], so successive force levels must differ by at least 10% to be perceptually different. In the task, each target required 25% more torque than the preceding target, to increase the likelihood of making the targets feel perceptually distinct. The target distances and their expected relative torque or deformation extents (according to equation 1) are shown in Table 1 and Table 2..

3.1.3 Study 1

In the first study, the target distances were defined in terms of the required torque, which were kept constant across devices. They are shown in Table 1, along with the resulting angle of deformation across the three devices. In our measurements, the level of torque required to reach the furthest target with the *Medium* device was 10.06 N·m. In equation 1, this torque would result in a maximum angle of deformation of 7.6°. That same maximum torque value would require deforming an angle of 22.35° with the *Soft* device, but only 4.02° with the *Hard* device. The rest of target distances were also defined taking the torque required by the *Medium* device as reference. In each case, the 10 bits of sensing range on each side of the device were distributed over the complete bend range, by varying the amplification. Therefore angle resolutions for *Soft*, *Medium*, and *Hard* were respectively 0.022°, 0.007° and 0.004°, on average.

Table 1: Study 1 Target Distances, with required torque and resulting angle of deformation, across the devices.

			Angle (°)		
Target	**Distance**	**Torque**	**Soft**	**Medium**	**Hard**
1	1.2	1.35	3	1.02	0.54
2	1.5	1.69	3.75	1.275	0.675
3	1.87	2.10	4.675	1.5895	0.8415
4	2.34	2.63	5.85	1.989	1.053
5	2.93	3.30	7.325	2.4905	1.3185
6	3.66	4.12	9.15	3.111	1.647
7	4.58	5.15	11.45	3.893	2.061
8	5.72	6.44	14.3	4.862	2.574
9	7.15	8.04	17.875	6.0775	3.2175
10	8.94	10.06	22.35	7.599	4.023

3.1.4 Study 2

In the second study, the target distances were defined in terms of the required deformation angle, which are shown in Table 2, along with the torques required to reach that angle across the devices. For each target distance, the target deformation angle was set to the same angle of deformation from the *Medium* device in Study 1. This would result in *less* required torque for the same bend angle when bending the *Soft* device and *more* required torque for the same deformation angle when bending the *Hard* device.

Table 2: Study 2 Target Distances, with required deformation angle and resulting torque, across the devices.

			Torque (N·m)		
Target	**Distance**	**Angle**	**Soft**	**Medium**	**Hard**
1	1.2	1.02	0.46	1.35	2.55
2	1.5	1.275	0.57	1.69	3.19
3	1.87	1.5895	0.72	2.10	3.97
4	2.34	1.989	0.90	2.63	4.97
5	2.93	2.4905	1.12	3.30	6.23
6	3.66	3.111	1.40	4.12	7.78
7	4.58	3.893	1.75	5.15	9.73
8	5.72	4.862	2.19	6.44	12.16
9	7.15	6.0775	2.73	8.04	15.19
10	8.94	7.599	3.42	10.06	19.00

3.2 Participants & Procedure

24 participants took part, with 12 in each study. Study 1 had 9 males and 3 females, aged from 25 to 42 (mean = 37). Study 2 had 6 males and 6 females, aged from 30 to 43 (mean = 36.33). The experiment lasted approximately 45 minutes and participants were sat in a padded office chair facing a computer monitor sat on a desk approximately 75cm away. They held the devices in both hands and were allowed to rest their elbows on the arms of the chair. They were deliberately stopped from resting the device on their lap/legs, as the friction of the hands rubbing against their legs/clothes could give further tactile feedback as to how much they are bending the device. The positions of the screen and the DUI-RP were such that participants could not see the device bending during the task. We used a within-subjects design for both studies, with all participants using all three DUI-RP devices in a counterbalanced order. Within each device condition, the participant targeted and maintained 40 target distances presented in a random order: each of the 10 distances were targeted twice, in each direction (i.e. bending up and down).

Each trial started with the device in the neutral, flat position. After bending to, and maintaining, a target distance for the full 8 seconds (4 with visual feedback, 4 without), the word "release" appeared onscreen to tell the participant to stop deforming the device to allow the cursor to return to parking. The cursor became visible again upon entering parking and had to remain within parking for 2 unbroken seconds for the next target trial to begin.

The Independent Variables were: *Device Stiffness* (Soft, Medium and Hard), *Target Distance* (10 distances) and *Feedback* (Visual and Non-Visual). The Dependent Variables were: *Error* (average distance of cursor to target distance/deformation), *Variance* (standard deviation of input during the sustain phase only) and *Subjective Workload Estimation* (NASA TLX) ratings, which were taken after each Device condition. For the analysis of the *variance* and *error* data, we ignored the first 500ms of input from the beginning of the sustain phase, to minimise excess movement in the data as the participant transitioned from bending to sustaining. Subjective user reports were also elicited from a post-study interview, which included questions on the *ease of use* of each device and the *difficulty* of any aspect *of the task*; whether they *appreciated bending up and down differently* and whether they had a *preference* for any of the devices.

As some of the data did not fit a normal distribution (infrequent extreme values led to strong positive skew in the data set), we used non-parametric analyses, specifically the Friedman test for non-parametric ANOVA equivalent and Wilcoxon *T* tests for pairwise comparisons. Although the use of non-parametric tests increases the validity of results gained from non-normal data, they are limited by their inability to examine interaction effects. We also add precedence to median values, as the mean is biased by (dragged towards) the skew in the data set. Despite this, in cases where median values were near-equal yet a significant difference exists, means were also shown for illustration. For normally distributed data, ANOVA and means were used.

4. STUDY 1 RESULTS

4.1 Error

Friedman's Test showed no significant main effect of Device Stiffness on Error (χ^2 (2)=0.865, p>.05). Median Error values for each device were 0.1 (SD = 0.467), 0.105 (SD = 0.244), and 0.111 (SD = 0.263), for the Soft, Medium and Hard device respectively. Error box plots can be seen in Figure 4.

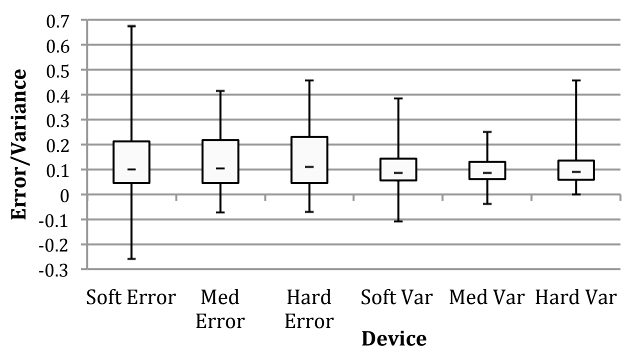

Figure 4: Box plots for Error and Variance across all three devices in Study 1 (tails show 1 SD).

Friedman's Test showed a significant main effect of Distance on Error (χ^2 (9)=27.966, p = .001). Median Error values for each

Distance are shown in Table 3. Post hoc Wilcoxon *T* tests were carried out, adjusting the required alpha for significance to p<=0.0011, and significant differences were found comparing Distance D9 with each of D1, D2 and D7; and D10 with both D1 and D2. In all cases D9 and D10 had higher Error than the others.

Table 3: Median Error and Variance for all Target Distances (TD) in both studies, with standard deviation in brackets.

	Study 1		Study 2	
	Error	Variance	Error	Variance
TD 1	0.108 (0.134)	0.065 (0.064)	0.116 (0.159)	0.062 (0.052)
TD 2	0.110 (0.189)	0.072 (0.072)	0.11 (0.165)	0.065 (0.047)
TD 3	0.091 (0.175)	0.074 (0.094)	0.127 (0.173)	0.068 (0.06)
TD 4	0.106 (0.167)	0.08 (0.119)	0.117 (0.179)	0.068 (0.038)
TD 5	0.093 (0.186)	0.085 (0.076)	0.108 (0.202)	0.077 (0.136)
TD 6	0.090 (0.235)	0.089 (0.123)	0.102 (0.169)	0.08 (0.050)
TD 7	0.103 (0.226)	0.09 (0.108)	0.098 (0.166)	0.088 (0.073)
TD 8	0.102 (0.392)	0.106 (0.180)	0.099 (0.158)	0.086 (0.057)
TD 9	0.134 (0.650)	0.115 (0.182)	0.1 (0.147)	0.091 (0.068)
TD 10	0.125 (0.555)	0.117 (0.443)	0.096 (0.151)	0.082 (0.065)

A Wilcoxon pairwise comparison showed a significant effect of Feedback on Error (*T*=98484.0, p<.001), as Non-Visual Feedback (median = 0.190, SD = 0.434) produced higher Error than Visual Feedback (median = 0.067, SD = 0.160). Effect size was medium to large, *r* = 0.49. Effect size was measured using Pearson's correlation coefficient (*r*), following Cohen's [2] interpretation guidelines of 0.1 for small effect, 0.3 for medium and 0.5 for large.

4.2 Variance

There was also no effect of Device Stiffness on Variance, using Friedman's Test (χ^2 (2)=0.281, p>.05). Median Variance values were 0.087 (SD = 0.246), 0.087 (SD = 0.158), and 0.089 (SD = 0.126), for the Soft, Medium and Hard Devices respectively. Variance box plots can be seen in Figure 4.

Friedman's Test showed a significant main effect of Target Distance on Variance (χ^2 (9)=281.495, p < .001). Median Variance values for each Distance are shown in Table 3. Post hoc Wilcoxon *T* tests were carried out, adjusting the required alpha for significance to p<=0.0011. Significant differences were found between multiple pairs of Distances (D): D1 vs. D4-D10 (inclusive); both D2 and D3 vs. D6-D10; D4 and D5 vs. D8-D10, D6 vs. D9, D10; and D7 vs. D8-D10. In general Variance increased as Distance increased.

A Wilcoxon *T* test showed a significant effect of Feedback on Variance (*T*=472866.0, p<.05). Non-Visual Feedback had a median Variance of 0.083 (SD = 0.193), Visual Feedback had a median of 0.090 (SD = 0.174). Effect size was very small, *r* = 0.04.

4.3 Subjective User Reports

One-way repeated-measures ANOVA showed that Device Stiffness significantly influenced reports of subjective physical demand ($F_{2,22}$= 4.020, p<.05), however post hoc Bonferroni comparisons found no significant differences between Devices. The Medium device produced higher reports of Physical Demand (mean = 9.89) than both the Soft (mean = 8.87) and the Hard (mean = 8.92) Devices. No other TLX scales significantly varied across Devices.

"Getting to near targets was easy but maintaining them was hard, particularly with the [Soft Device]"

11 participants gave this kind of comment. They believed, sometimes for different reasons, that it required little mental or physical effort to move the cursor from parking into close proximity of the nearest targets (by bending the device), but that keeping the cursor as motionless as possible during the sustain phase was more challenging than while sustaining at further target distances. This was attributed to both the Soft device and the Hard device but for different reasons. The Soft device was difficult because being easier to bend led to unintended bending, resulting in overshooting targets at low levels, while the Hard device was difficult because, as it bent so little, it provided little to no haptic feedback concerning input and small changes in deformation angle led to large movements onscreen. In converse, it can be deduced that extra haptic feedback gained from bending the Hard device to further targets may have provided more information concerning input.

"Getting to and maintaining furthest targets was difficult"

6 participants made this, or a similar, comment about the Hard device predominantly. While the nearest targets were difficult to maintain because of too much or too little response from the device, the furthest targets were difficult to maintain due to the physical effort required in bending the devices. This suggests that the middling target distances/torque (approximately 2-6 N·m, 1°-3° rotation for the Hard device) may represent a suitable range for input on more rigid devices.

"The devices felt different but none were "difficult" "

Although a small number of participants reported that they did not notice a physical or mechanical difference between the devices, most reported that they did feel physically different, and most often in terms of stiffness. However, many reported that, although the devices felt perceptually different, they wouldn't consider any device actively "difficult" to use, only comparatively so.

When asked if they had a preference for any device, 6 (50%) said the Soft device, 2 (16.7%) said the Medium device and 1 (8.3%) said the Hard. 3 (25%) had no preference.

5. STUDY 2 RESULTS

5.1 Error

Friedman's Test showed a significant main effect of Device Stiffness on Error (χ^2 (2)=9.231, p=.01). Median Error values for each Device were 0.107 (mean = 0.163, SD = 0.174), 0.1 (mean = 0.151, SD = 0.160), and 0.112 (mean = 0.168, SD = 0.168), for the Soft, Medium and Hard Devices respectively. Post hoc Wilcoxon *T* tests, with an adjusted necessary alpha for significance of p< = 0.0167, showed that the Medium Device differed significantly from both the Soft Device (very small effect size, *r* = 0.05) and the Hard Device (very small effect size, *r* = 0.08). Error box plots can be seen in Figure 5.

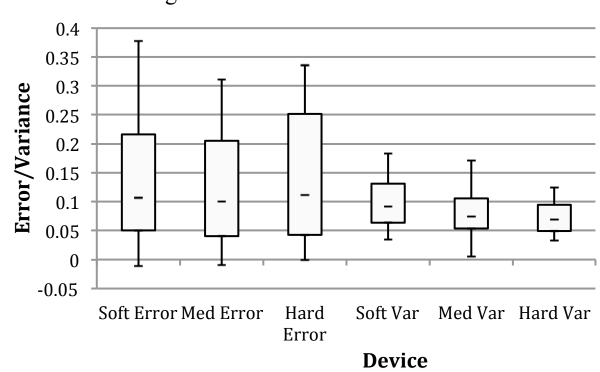

Figure 5: Box plots for Error and Variance across all three devices in Study 2 (tails show 1 SD).

Friedman's Test showed no significant main effect of Target Distance on Error (χ^2 (9)=6.626, p>.05). Median Error values for each Distance are shown in Table 3. A Wilcoxon pairwise comparison showed a significant effect of Feedback on Error (*T*=107563.0, p<.001), as Non-Visual Feedback (median = 0.182) produced higher Error than Visual Feedback (median = 0.064). Effect size was medium to large, *r* = 0.48.

5.2 Variance

Friedman's Test showed a significant main effect of Device Stiffness on Variance (χ^2 (2)=189.015, p<.001). Median Variance values for each Device were 0.091 (SD = 0.074), 0.075 (SD = 0.083), and 0.069 (SD = 0.046), for the Soft, Medium and Hard Devices respectively. Post hoc Wilcoxon *T* tests, with an adjusted necessary alpha for significance of p<=0.0167, showed that all Devices differed significantly from each other, with small to medium effect sizes for Medium vs. Soft (*r* = 0.24) and Hard vs. Soft (*r* = 0.3) and a small effect size for Medium vs. Hard Device (*r* = 0.09). Variance box plots can be seen in Figure 5.

Friedman's Test showed a significant main effect of Target Distance on Variance (χ^2 (9)=219.774, p < .001). Median Variance values for each Distance are shown in Table 3. Post hoc Wilcoxon *T* tests were carried out, adjusting the required alpha for significance to p<=0.0011, and significant differences were found between multiple pairs of Distances (D): both D1 and D2 vs. D5-D10 (inclusive); D3 and D4 vs. D6-D10; and D5 and D6 vs. D9. In general Variance increased as Distance increased.

Wilcoxon *T* test showed a significant effect of Feedback on Variance (*T*=468340.0, p=.001). Non-Visual Feedback (median = 0.079, mean = 0.096) appears to have produced more Variant input than Visual Feedback (median=0.076, mean=0.088). Effect size was very small, *r* = 0.06.

5.3 Subjective User Reports

One-way repeated-measures ANOVA showed that Device Stiffness significantly influenced reports of subjective physical demand ($F_{2,22}$= 4.434, p<.05), however post hoc Bonferroni comparisons found no significant differences between Devices. Reports of Physical Demand decreased as Device Stiffness decreased, with mean values of 10.25 (SD = 5.36), 8.33 (SD = 3.87) and 6.17 (SD = 3.21) for the Hard, Medium and Soft Devices respectively. No other TLX scales significantly varied across Devices.

"Maintaining furthest targets requires a lot of effort", "the [Hard Device] was hard"

The frequency of this comment and the language used in Study 2 suggest it was a more noticeable issue than in Study 1, although mainly with the Hard device, as well as the Medium device to a lesser extent. In order to reach the furthest targets from parking, a lot of physical effort was needed. Interestingly, in spite of the increased effort, there were conflicting comments on the ease of use, with some believing the Hard device was easier to control, and others believing it was more difficult to control. Whereas it may be more physically challenging to deform, relative changes in deformation angle would have led to less cursor movement than with other devices, providing a more stable input.

"The [Soft Device] felt very sensitive"

In a similar manner to Study 1, the Soft device proved more challenging to maintain nearer targets, due to requiring very little amount of bending, a complaint leveled at the Hard device in Study 1. In fact, the Soft device was frequently considered sensitive in general, with very small changes in input/deformation angle resulting in large changes in cursor position on screen. This made targeting difficult across a wider range of targets, not only the nearest ones to parking, and especially when no visual feedback was present.

In terms of user preference a similar pattern to Study 1 emerged: 5 (41.67%) preferred the Soft device, 3 (25%) preferred the Medium device and 2 (16.67%) preferred the Hard device. 2 (16.67%) had no preference.

Table 4: User preferences for each device, in both studies.

	Soft	Medium	Hard	None
Study 1	6 (50%)	2 (16.7%)	1 (8.3%)	3 (25%)
Study 2	5 (41.67%)	3 (25%)	2 (16.67%)	2 (16.67%)

6. DISCUSSION

6.1 Device Stiffness

The first Research Question (RQ) we sought to answer in this paper was: "*Does device stiffness influence our ability to accurately deform a device?"*. If we consider only the quantitative data and results, it would appear that the answer is generally "no", stiffness did not have a strong impact on user performance, at least concerning the range of material stiffness we used (i.e. 0.45 N·m/rad, 1.3 N·m/rad and 2.5 N·m/rad). There were no significant differences between devices in precision of control when the range of required torque was kept constant in Study 1. Therefore, within the range of 1.35-10.06 N·m, greater or lower device stiffness did not hamper user ability, but neither, it seems, did the potential extra haptic feedback from more physical deformation of the device lead to better performance (remember Soft > Medium > Hard in maximum deformation angle in Study 1).

Regarding Study 2, when the range of deformation angle was kept constant, even though there were statistically significant differences between devices in terms of both Error and Variance, the practical differences were very small. Median Error values were near-equal and median Variance and mean Error values varied by only 0.01-0.03, less than 1% of the interaction space. Therefore, considering only performance and the stiffness ratings used here, device rigidity does not appear to be an important factor. These results echo those from Kildal [12], where small performance differences were found between device stiffness.

However, focusing on participants' subjective reports provides more illuminating information, and goes some way to answering half of *RQ3: "How [does] device stiffness…influence ease, comfort and enjoyment of use?"* An important aspect of our investigation into deformable device design was user perception and preference. In both studies, these did not support equality across the devices, as was suggested by the quantitative results. In Study 1 the majority of participants reported that the devices felt perceptually different in terms of their stiffness, and the significant effect of Device on TLX reports of Physical Demand reinforce this subjective distinctiveness. These participants tended to report similar benefits and liabilities for the Soft and Hard devices. They generally felt that the Soft device was physically easier to bend (and so move the cursor) but that this very softness made it more difficult to maintain a constant angle of bend. Conversely the Hard device was more difficult to bend (particularly to large angles) but that it was easier to maintain target forces.

The common report that none of the devices was considered challenging to use supports the equal quantitative results. However, the subjective opinions, and the finding that 6 (50%) participants expressed preference for the Soft device while only 1 (8.33%) preferred the Hard, suggest that physical comfort and low effort may be more important to users than high precision in deformable device design, a finding that supports Lee *et al.*'s [15] assertion that users naturally prefer softer manipulation devices.

A similar trend emerged from Study 2, where the Hard device required a much larger range of torque values (therefore requiring more effort), but the Soft a much smaller range. In this case stronger negative comments were made about the Hard device, in terms of the physical discomfort, backed up by TLX ratings of Physical Demand, which increased as device stiffness increased. Meanwhile the Soft device was considered by some to be overly sensitive leading to difficulty in maintaining precision across a range of targets. Despite this difficulty, 5 (41.67%) participants still preferred the Soft device, with only 2 (16.67%) preferring the Hard. The Hard device had the lowest Variance of all devices in Study 2 but, again, it appears that physical comfort trumps precision.

Interestingly, there were a small number of hedonic/experiential comments made about the Soft device, such as "the [touch] experience felt nicer" and "more forgiving" and "engaging". These kinds of comments were not made about the Medium or Hard device, so it appears that softer deformable devices are more likely to provide enjoyable and approachable deformable interfaces. Given the apparent trade-off between comfort/physical effort and precision, there is likely to be a balance or compromise, perhaps in the guise of the Medium device, whose stiffness and control gained few negative comments but whose praises were rarely sung as well. At least in our case, a stiffness of 1.3 N·m/rad may be suited to an input range of approximately 1-10 N·m (1°-8° of deformation). Previous focus groups during development of the kinetic DUI-RP also elicited preference for the Medium device for very similar reasons as described here.

Many of these results echo those of Kildal [12]. He also found small performance differences between devices of different stiffness, accompanied by a perception that none of the devices were difficult to use. Participants in that study also strongly preferred softer devices (due to the higher effort levels required to bend the hard device) even though the soft device led to occasional control issues. The congruence of results strongly supports the notion, also put forward by Lee *et al*. [15], that softer devices are more suitable for deformable interaction, although the softest devices may not be optimal from the point of view of perceived sense of control.

6.2 Deformation Range

In answer to *RQ2, 'Does the extent of physical deformation influence our ability to accurately deform a device?',* there was a pronounced effect of target distance/deformation angle on performance measures. There was no effect of distance/angle on Error in Study 2, however in terms of Error in Study 1 and Variance in both studies, precision of input dropped as the deformation angle increased. In other words greater extents of bend were generally more difficult to apply and maintain accurately. This difficulty was echoed by subjective user comments, which addresses the second half of *RQ3: 'How [does]…deformation extent influence ease, comfort and enjoyment of use?'*.

A point to note is that, even though more comments were made about the difficulty in targeting using the Hard device in Study 2, angle/distance did not affect Error in this study. Even though the Hard device was physically harder to bend, the reduced gain/sensitivity in Study 2 may have made precise targeting easier. Despite the general decrease in precision with increasing target distance, participants also complained at finding the nearest targets difficult to maintain using the Hard device in Study 1. Research has suggested that the Just Noticeable Difference for rotation at both the wrist and elbow joints is 2° [25], which is likely to be larger than the extent of rotation required to reach the nearer targets. In this case the individual would have had more difficulty in judging the extent of applied torque due to the small differences between targets. As mentioned above, maintaining near targets was also difficult with the Soft device, as high flexibility led to unintended changes in input.

Therefore deformable devices, particularly those made from materials more rigid than perhaps ~2.0 N·m/rad, may do well to require only moderate extents of bend, approximately 1°-3° (with each hand) in our case, in order to support precision and comfort. In contrast, devices made from soft materials (0.45 N·m/rad here) are recommended to require bends greater than approximately 3° (per hand). As user preference for the Soft device testifies, allowing more comfortable interactions may result in more engaged users.

6.3 Feedback

In line with previous HCI and psychophysics research [6, 7, 16, 19], removing visual feedback concerning the extent of input led to significantly higher Error and Variance (although the effect of Variance was weak). From these results it appears that the cutaneous and kinaesthetic feedback gained form bending the device was insufficient to maintain a target force as precisely as when presented with external feedback. One pattern of behaviour is interesting and worthy of note. Recall that proceeding from the visual feedback phase to the non-visual feedback phase is similar to traditional force-matching tasks, where the participant has to judge the magnitude of an externally specified target force and match it with an internally generated force magnitude. The increase in Error without visual feedback was much larger than the increase in Variance, and so it appears that removing visual feedback makes it more difficult to match an abstract externally dictated target force/angle (Error), but maintaining an internally generated force/angle (Variance) is perhaps easier.

Given these results, the answer to *RQ4, 'Is haptic feedback from device deformation sufficient to accurately maintain force output or is external feedback necessary?'* might appear to be a strong "no", however it might depend more on the definition of "sufficient". While the Error more than doubled under non-visual feedback and Variance also suffered, the 'real world' differences were still small, at around 3% of the interaction space. Therefore it is not unreasonable to suggest that eyes-free input on deformable devices such as the Kinetic DUI-RP is feasible, as long as the interaction includes suitable error margins, such as the width of a target. However, our research here did not look at "from-0" non-visual interaction, where the participant would have to move to a target deformation extent from rest/parking with no visual cues at all. This task would better indicate whether eyes-free interaction is possible.

Although there were statistically significant differences, it was surprising that device stiffness [1, 10, 22] and feedback did not have strong real-world influences on control. However it may simply be that the range of stiffness used was not wide enough to significantly influence performance, as we did not have a truly rigid device or a particularly loose device. The comparable performance may also be a product of the task, as non-visual maintenance of a target bend was from a visually-supported position: they simply had to avoid excess movement. Larger performance differences may have been apparent if the task had provided little or no visual feedback, to require participants to rely more on haptic feedback. With these in mind, future work should test a wider range of material stiffness and 'from-0' non-visual interaction with deformable devices, to get a better perspective on whether stiffness and deformation extent truly influence performance, or simply influence user preference. The use of more realistic tasks would also be of benefit, as the task used here was abstract and highly controlled.

7. CONCLUSIONS

This paper presented two studies using a mobile phone-shaped deformable device: Kinetic DUI-RP. It looked at how the device stiffness and the required extent of deformation influenced user precision and preference in a force-matching/targeting task. The purpose was to identify if design materials or interaction requirements might result in inaccurate or undesirable deformable interfaces. It also tested the influence of both external visual feedback and the inherent haptic feedback gained from bending a deformable device by requiring participants to match forces with- and without visual feedback.

It found that, while the range of material stiffness used did not markedly influence performance, user preference was strongly influenced and suggested more rigid/stiff materials were less desirable as they were uncomfortable to bend beyond 3° or 4° per hand, with soft materials allowing for a more comfortable and engaging interface. Also very small (<1° per hand) deformations were difficult to maintain accurately using both soft and stiff materials, so should also be avoided. The removal of external visual feedback resulted in significantly more error-prone control, but performance remained good enough to suggest that haptic-only non-visual interaction might be feasible for deformable devices.

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