Fitts' Law and the Effects of Input Mapping and Stiffness on Flexible Display Interactions

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ABSTRACT

In this paper, we report on an investigation of Fitts' law using flexible displays. Participants performed a one-dimensional targeting task as described by the ISO 9421-9 standard. In the experiment, we compared two methods of bend input: position control and rate control of a cursor. Participants performed the task with three levels of device stiffness. Results show that bend input is highly correlated with Fitts' law for both position and rate control. Position control produced significantly higher throughput values than rate control. Our experiment also revealed that, when the amount of force applied was controlled, device stiffness did not have a significant effect on performance.

Author Keywords

Organic User Interfaces, Deformable User Interfaces, Fitts' law, stiffness, flexibility, deformation, bend input.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

With the introduction of Organic User Interfaces (OUIs) [10], research into flexible displays and their interaction techniques has become increasingly widespread. One of the primary tenets of OUIs is that *form follows flow*: the shape of a device can be changed and is linked to its function. With one style of OUIs, users reconfigure a device to present different views or options that are appropriate to its shape [7,25]. In other cases, bending or deforming a display is used as a direct input method to signify gestures [17], manipulate photos [14], scroll through a list [3], or move a cursor [15]. In effect, a user modulates the shape of an OUI to suit the needs of their task.

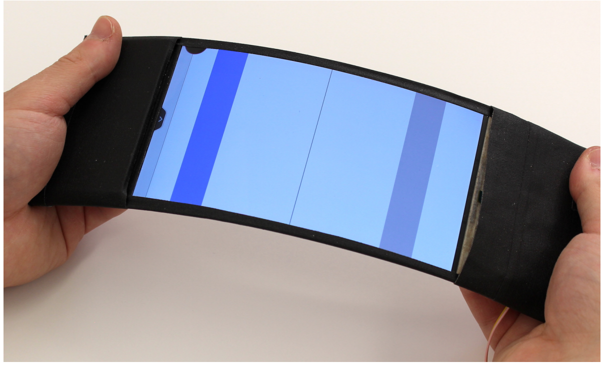

Figure 1. Prototype flexible smartphone displaying a Fitts' law targeting task.

Despite it being a developing research area, there have been few studies that have thoroughly explored targeting performance on flexible displays using bend gestures as input. As an emerging interaction technique, it is currently unknown if, and to what extent, bend input follows Fitts' law [6]. And for the same reason, it is difficult to compare the performance bandwidth of this technique to existing devices.

Designers must also consider the physical qualities of an interface in this new paradigm of shape change. An essential characteristic of flexible displays is their *stiffness*: a property that influences the degree to which a device can be deformed, and in turn, how much effort a user must apply to do so. This physical quality can influence how much users enjoy using an interface [17] and can have effects on task efficiency [15]. It is also important to understand how flexible a device must be to provide efficient input because the more flexible a display is, the more likely it is to fail in product.

In this paper, we report on an investigation of Fitts' law on flexible displays (Figure 1). Participants performed a standard one-dimensional targeting task [11]. During the experiment, participants moved a cursor using two methods of bend input: position control and rate control of a cursor. Participants also performed the task with three levels of device stiffness: Soft, Medium, and Hard. Our key findings include that bend input is highly correlated with Fitts' law for both position and rate controlled cursors (r = 0.92, 0.96). We found that position control produced significantly faster movement times, with 78% higher throughput. Our

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experiment also revealed that, when the amount of force applied was controlled, device stiffness did not have a significant effect on task performance.

RELATED WORK

Fitts' Law and Deformation

Ahmaniemi et al. [1] conducted an experiment where participants performed a size-matching task by bending a flexible display. The authors claim that, to their knowledge, it was the first analysis of Fitts' law that used deforming a display as input (although they did not use a one-dimensional targeting task following the ISO 9421-9 standard [11]). They report that an absolute mapping was faster, but resulted in a lower correlation to Fitts' law ($r^2 = 0.206$) than the slower, relative mapping ($r^2 = 0.626$)—correlations too low to constitute a valid fit with Fitts' law. In addition, their analysis was based on time and did not include throughput. Overall, they conclude that even though these techniques had a poor fit to the Fitts' law model, bending can be useful as an interaction method for controlling continuous parameters, provided that it is implemented carefully.

Given that Ahmaniemi et al. claim to have presented the first Fitts' law analysis of bending a flexible display, the closest prior evaluations might be considered those that examined pressure input. Lee et al. [16] found that tangential force on a touch screen produced relatively high correlations ($r^2 = 0.90$-0.94). Ramos et al. [24] report that their "pressure widgets", using a force-sensitive stylus, also provided a fairly good fit ($r^2 = 0.84$) in a serial Fitts' law task. Scott et al. [28] presented a rigid device that could sense twisting and stretching forces. They report that tasks performed with this device had a very low fit to Fitts' law; they argue that for many isometric devices, the model is a poor predictor because limb movement is negligible [19].

Other work has considered Fitts' law on flexible displays, but examined deformation as a variable rather than as a method of controlling navigation. For example, Dijkstra et al. [5] conducted an experiment where participants pointed at a flexible substrate held in their non-dominant hand. The authors found that throughput was lower on the more flexible areas of the surface, as compared to the more rigid zones created by holding the display in certain grips. These flexible zones also produced lower throughputs in a dragging experiment performed on the surface.

Performance of Deformation

Compliance to Fitts' law is only one method to determine the suitability of deformation for a given task. Burstyn et al. [3] investigated the relationship between bend and touch interaction on a flexible display with a page flipping / list navigation task. They found that an absolute mapping was faster than a relative mapping for both bend and touch input, results consistent with Ahmaniemi et al.'s size matching task [1]. Their second experiment used both bend and touch together in a multi-scale Fitts' law task [8]. Results showed that using the two methods of input concurrently, i.e., touch for targeting and bend input for zooming the canvas, outperformed touch alone. Although the task followed the conventions of a Fitts' law task, no Fitts' law analysis was performed and, in addition, bend input was not used for targeting. Similarly, Kildal et al. [14] created a flexible interface that incorporated both twisting and touch input. Although they found no differences in task performance between the combined bend/touch and touch alone, participants reported that the combination felt more intuitive and accurate.

As we have seen, Dijkstra et al. [5] provided evidence that the flexibility of a surface can affect the performance of touch interaction. Along these lines, Bacim et al. [2] presented a study where participants pressed into flat and hemispherical deformable surfaces. The experiment revealed that participants are capable of deforming to precise depths, and that visual feedback can significantly improve this precision and accuracy. Without this visual feedback, however, participants had difficulty differentiating between very small amounts of pressure or force. Similarly, Sato et al. [27] created ClaytricSurface, a deformable multi-touch tabletop that could modify its stiffness and produce flat and hemispherical (or arbitrary) touch surfaces. The authors conducted a touch accuracy test and found that participants produced larger touch-location spreads when the surface was soft compared to when it was rigid. These results suggest performance can vary based on the amount a surface can deform.

Effects of Stiffness

Stiffness (or rigidity, or flexibility) is an important descriptor of deformable interfaces [25]. A number of researchers have sought to understand how people experience stiffness and if it can affect user performance.

Nakagawa et al. [20] presented MimicTile, a deformable mobile interface that can vary its stiffness based on user input. Based on a small pilot study, they report that participants could differentiate between three levels of stiffness with a 90% accuracy rate. With SqueezeBlock, a handheld haptic device, Gupta et al. [9] found that participants could accurately identify the two extremes of five levels of stiffness, but often overestimated the middle three values.

Lee et al. [17] conducted a series of user studies comparing how users deform flexible materials, such as paper, elastic cloth, and plastic sheets. Among their results, they found that participants enjoyed highly flexible materials: the more flexible the condition was, the greater preference they reported. In addition, gesture agreement was more consistent for the more flexible materials.

Stiffness also has a measurable effect in navigation tasks using bend interaction, for example when moving a cursor or when zooming. Kildal [13] compared three flexible devices (without displays) each with a different level of stiffness (0.45, 1.3, and 2.5 *N·m/rad*). In a zooming task, participants were significantly slower with the stiffest material than the medium or lowest rigidity. Using the same three devices, Kildal and Wilson [15] performed two experiments, observing participants' ability to maintain specific levels of force or specific deformation angles. They measured participants' error (difference between applied and target force/angle) and variability. When users had to maintain a specific angle, the authors found that the three devices differed in both error and variability. More importantly, the authors found that stiffness was not a significant factor for either measure when maintaining target forces. Overall, this suggests that designing for specific forces, rather than deformation angle, can provide a consistent experience across bendable devices.

EXPERIMENT RATIONALE

This work is motivated by our primary question: does bend interaction on flexible displays follow Fitts' law? From there, our goal was to investigate if and how two parameters affect a flexible display's suitability and throughput for Fitts' law: its input mapping and its stiffness.

Fitts' Law

By 1954, Paul Fitts had observed that rapid aimed movements become slower with increased accuracy demand [6]. He described this phenomenon with a simple mathematic equation, currently referred to as Fitts' law:

$$MT = a + bID$$

or

$$MT = a + b\log_2\left(\frac{A}{W} + 1\right)$$

where *MT* is the movement time required to reach a target of a specific index of difficulty (*ID*). *ID* describes a target with width *W*, whose center is at amplitude *A* away from a starting position. Here, a and b are empirically discovered constants, typically specific to a single participant using a given input method. The +1 constant is advocated by MacKenzie as the Shannon formulation of Fitts' law [18], which improves the fit for low *ID*s.

Fitts' law is a very robust model, one that has become a standard tool to investigate the efficiency of novel input methods and interaction techniques using rapid aimed movements. Specifically, HCI often uses *throughput* (measured in bits per second) as a common benchmark, a single statistic that combines multiple measurements into a dependent measure. An advantage of calculating throughput is that it corrects for both speed and accuracy.

Existing investigations of target acquisition with deformable interfaces (specifically bending) have had inconclusive results. Given that Fitts' law has become such a standard tool, we felt it was important for the future development of OUIs to better understand how users perform rapid aimed movements with flexible displays. One interesting question is how flexible a smartphone must be to provide enjoyable and efficient bend input – while remaining robust enough to be reliably manufactured.

Input Mappings

Like many input devices, interacting with flexible displays is more specified than the physical act of bending. One must take into consideration the transfer function that maps sensor input into display output. In this study, we investigate two methods of controlling a cursor, which we have adapted for bend input:

Position Control

For a flexible display, position control (or absolute mapping) means that a specific bend angle corresponds to a specific cursor position on the display. In other words, the full range of bend sensor values are directly mapped onto the number of pixels on the display. In our experiment, the cursor only moves horizontally. When the display is at rest, the cursor is in the center of the display. The more a user bends the display into a convex shape, the further left the cursor is positioned. Bending the display into increasingly concave angles moves the cursor to the right.

Rate Control

In rate control (or relative mapping), the position of the cursor is controlled through its velocity (i.e., speed and direction). When a user bends the flexible display into a convex shape, the cursor moves towards the left. Bending it into a concave shape moves the cursor to the right. The speed of the cursor is mapped to the extent of the bend via an established sinusoidal easing function [22]:

$$f(x) = 1 - \cos\left(x * \frac{\pi}{2}\right),\ \ x: [0, 1]$$

Subjects in our pilot studies found that this easing function was more natural than a linear mapping as it prevented small fluctuations of applied torque from producing unintentional cursor movements.

Zhai [32] enumerated the benefits and drawbacks of these input mappings – many of which Ahmaniemi et al. found were in agreement for deformable interfaces [1]. Given that neither technique was found to be superior in all situations, we chose to continue to explore rapid aimed movements with both position and rate control.

Stiffness

Zhai [32] also distinguishes between two types of devices: *isotonic* and *isometric*. One of their main differences is their *stiffness*, i.e., how much they oppose physical displacement. Isotonic devices (e.g., a mouse) have a constant low resistance, while isometric devices (e.g., IBM Trackpoint [26]) resist almost all displacement and operate only through applied force. Flexible displays often fall under a third category, *elastic* devices, which have a resistance that increases proportionally with displacement (i.e., following Hooke's law).

Elastic devices with different degrees of stiffness fall onto different points on the isotonic-isometric spectrum.

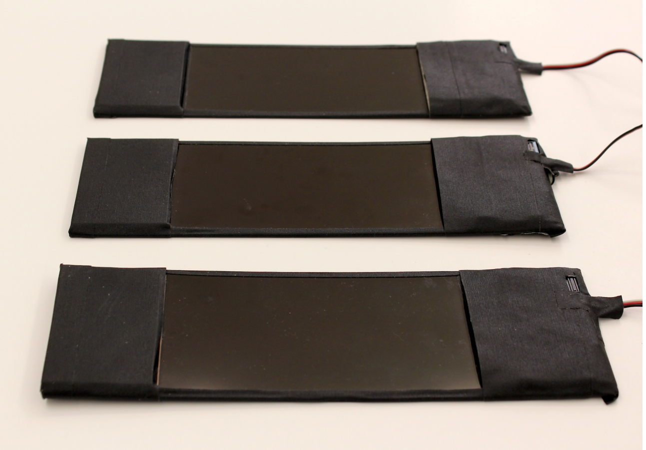

Figure 2. Three prototype flexible smartphones with different levels of stiffness. Top to bottom: Soft (0.29 *N·m/rad*), Middle: (0.57 *N·m/rad*), Hard (1.31 *N·m/rad*).

Previous investigations provide evidence that higher amounts of resistance can afford better rate control, while lower resistance affords more proprioceptive feedback of displacement and can be more suitable for position control [32]. We chose to investigate both techniques to reveal further insights into the effects of stiffness on Fitts' law performance.

Considering both shape and force, we examined three levels of display stiffness. We refer to these levels as Soft, Medium, and Hard (0.29, 0.57, and 1.31 *N·m/rad*): a range that is, in general, less rigid than previous studies overall. Our Hard condition is similar to Kildal and Wilson's Medium device (1.3 *N·m/rad*), and their Soft device (0.45 *N·m/rad*) is approximately half way between our Soft and Medium conditions [13,15]. The devices were calibrated such that the same level of applied torque resulted in the same cursor movement. The maximum possible torque was 15.1 *N·m*, which would move the cursor to the edge of the display when using position control.

We chose this more flexible range of stiffness for several reasons. One consideration for OUIs is that shape and interaction are often linked; this prompted us to investigate interfaces that could be bent into a larger range of angles. This had the effect of lowering the amount of force required in our experiment overall, helping to reduce any potential effects of fatigue. In addition, these levels of stiffness enabled more paper-like form factors that might be more typical of future Organic User Interfaces [3,7].

APPARATUS

Hardware

Our experimental apparatus consists of three flexible smartphone prototypes (Figure 2). Each prototype consists of an Android 4.2 cellphone motherboard connected to an LG Display flexible OLED screen. The display measures 6.0" at the diagonal (135 mm by 77 mm), with a resolution of 1280x720 and a refresh rate of 60 Hz. It is mounted onto a flexible plastic substrate that extends 5 cm horizontally from either end of the display. The motherboard is mounted onto one of these bezels; the other side has a similarly sized piece of medium-density fiberboard to approximate symmetry in its weight and flexibility. We bonded an Omega Engineering strain gauge [21] to the middle of the plastic substrate to measure the extent and direction of bend input with a high degree of sensitivity. The strain gauge is wired to an amplifier that is sampled by a Teensy 3.1 microcontroller [23] at 96 MHz with 12-bit analog resolution.

Each of the three prototypes has a different stiffness level based on the thickness and composition of the plastic substrate used in its construction. The Soft device's substrate is 0.8 mm thick (0.29 *N·m/rad*). The Medium and Hard devices' substrates are 1.3 mm (0.57 *N·m/rad*) and 1.6 mm thick (1.31 *N·m/rad*), respectively (Figure 2).

Aside from the prototypes themselves, we provided a low-profile push button to select targets during the experiment. The participants held the button against the back of the prototype devices, in a comfortable location of their choosing.

Software

The microcontroller runs a simple low-pass weighted-average filter (based on Arduino's 'smooth' function) to stabilize the input signal and reduce noise from the ADC and amplifier. The flexible prototype is connected to a desktop computer for more precise control over experimental conditions. Our main experimental software is written in C++. This program polls the microcontroller for sensor values and converts them into updated cursor positions (~1 ms latency), based on the current display stiffness and input mapping. It also detects clicks from the push button and records performance data. Each flexible display prototype runs a basic Android client application that receives both cursor and target information from the desktop computer over Wi-Fi and draws them onto the display. The resulting display latency was ~30 ms.

EXPERIMENT

Participants

We recruited 12 participants to perform our experiment (8 male, 4 female). Their average age was 27.5 (*StdDev* = 4.1). All participants were right-handed and had experience using a smartphone. The experiment took 2 hours to complete and each participant was compensated with $20 for their time.

Experiment Design

We used a 3x2x12 factorial within-subjects design with repeated measures. Our factors were *display stiffness* (Soft, Medium, and Hard), *input mapping* (position control and rate control), and *index of difficulty* (12 *IDs* ranging from 1 to 4.9). Our dependent measures were throughput (bits per second), Pearson's *r* (-1.0 to 1.0), and movement time (milliseconds).

		Position Control					Rate Control				
		a	***b***	***r***	TP_{avg}	TP_{inv}	***a***	***b***	***r***	TP_{avg}	TP_{inv}
Soft	**Mean**	-38.03	288.47	0.933	3.74	3.75	275.87	398.70	0.963	2.06	2.62
	StdDev	199.85	82.60	0.024	0.42	1.07	145.39	77.65	0.027	0.28	0.58
Medium	**Mean**	50.84	264.50	0.919	3.72	4.00	288.33	363.03	0.958	2.23	2.90
	StdDev	172.27	68.62	0.045	0.68	0.86	122.88	78.45	0.030	0.40	0.71
Hard	**Mean**	-62.41	294.38	0.919	3.83	3.67	320.60	372.93	0.954	2.13	2.83
	StdDev	194.45	83.40	0.047	0.72	0.97	118.39	79.14	0.026	0.41	0.70

Table 1. Summary Fitts' law results for each *display stiffness* and *input mapping* combination, with regression coefficients (*a* and *b*), Pearson's *r* correlation coefficients, as well as both mean-of-means (TP_{avg}) and slope-inverse (TP_{inv}) throughput calculations.

Task Procedure

Participants were presented with a serial one-dimensional Fitts' law pointing task as described by ISO 9241-9 B.6.2.1 [11]. On a white background, two vertical ribbons appeared on the flexible display of a specified width and amplitude away from each other (Figure 1). We used three target widths of 40, 80, and 130 pixels, and four center-to-center amplitudes of 130, 460, 830, and 1140 pixels. For position control, each amplitude corresponded to rapidly targeting a specific level of torque (rather than maintaining a torque or a deformation angle [15]).

The current target was indicated with a light-blue color, the other was light grey. For each of the 12 *index of difficulty* conditions, a participant performed one block of 28 trials: each a single attempt to rapidly move the cursor to the target and click it. If the participant missed the target, the ribbon would briefly flash red as the new target was presented. The first 3 of these trials were used as practice and were not logged. In the remaining 25 trials per condition, the experimental software recorded their movement time and end-point positions.

Participants were instructed to click the targets as quickly and accurately as possible: moving rapidly while attempting to maintain an approximate 4% error rate [4]. After each block, participants were given feedback about their achieved error rate and their cumulative error rate for the current *display stiffness* x *input mapping* condition [31]. Participants performed one block of 25 trials for each of the 72 combinations of factors, resulting in a total of 1800 recorded trials. Condition order was counterbalanced between participants using a balanced Latin Square.

After each *display stiffness* x *input mapping* condition we asked participants to answer three 5-point Likert-scales about the following aspects of the condition: whether it was *efficient for performing the task*, *comfortable to bend*, and *easy to use*.

		Position Control	Rate Control
Soft	**Mean**	3.19	4.19
	StdDev	1.35	2.00
Medium	**Mean**	4.12	3.81
	StdDev	1.39	1.49
Hard	**Mean**	3.86	3.86
	StdDev	1.43	1.16

Table 2. Error rates for the six *display stiffness* and *input mapping* combinations.

Analysis Procedure

For each *display stiffness* x *input mapping* condition, 12 data points were calculated per participant based on the 12 *ID* conditions: pairs of average movement time (MT_e) and an effective index of difficulty (ID_e). ID_e is calculated through Crossman's adjustment for accuracy, one that generates an effective target width using the spread of end-point locations [4]. This calculation compensates for participants using different proportions of a nominal target width, based on its difficulty and their personal movement strategy. For each participant, these 12 adjusted data points were used to produce a Fitts' law model using linear regression and a Pearson *r* correlation coefficient. Table 1 outlines the mean model parameters and their variation for each condition.

Each subject's throughput (*TP*) for that condition was calculated in two ways. First, we used the mean-of-mean's approach (TP_{avg}) recommended by Soukoreff and MacKenzie [29]. We also calculated the throughput measures using the slope-inverse approach of $1/b$ (TP_{inv}). In both cases, a grand throughput for a *display stiffness* x *input mapping* condition was produced using the mean of the participant's individual throughputs. Table 1 outlines the grand throughputs for each condition.

This analysis was performed in a C++ application using procedures adapted from Wobbrock et al.'s open-source FittsStudy software [31].

Hypotheses

We hypothesized that position control would have faster movement times (*H1*) and therefore higher throughput (*H2*) than rate control. This prediction is based both on previous literature [1,3] and our own observations that the direct mapping allows users to navigate faster while maintaining the ability to make corrective sub-movements. With respect to display stiffness, we did not predict that we would find any differences between devices for either movement times or throughputs (*H3, H4*) as each device required the same amount of force to operate [15]. Based on prior investigations of Fitts' law on deformable interfaces, we also hypothesized that rate control would have higher correlations than position control (*H5*).

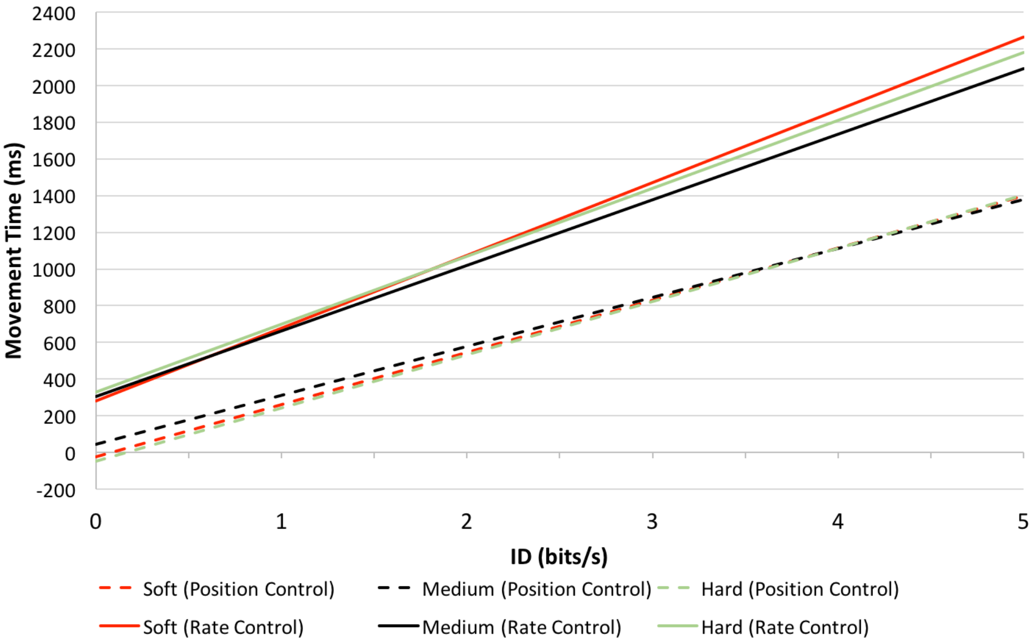

Figure 3. Best fit lines of combined subject data for each *display stiffness* and *input mapping* combination.

RESULTS

Fitts' Law Model

To analyze the resulting throughputs, we performed a repeated measures ANOVA on *display stiffness* (3) x *input mapping* (2) for both TP_{avg} and TP_{inv}. For TP_{avg}, the analysis found that *input mapping* was a significant factor ($F_{1,11}$ = 435.968, $p < 0.001$). We found a similar result for TP_{inv}: there was a significant main effect of *input mapping* ($F_{1,11}$ = 51.122, $p < 0.001$). Position control had significantly higher throughputs than rate control in both measures. The average absolute difference between input mappings was ΔTP_{avg} = 1.62 (*StdDev* = 0.09) and ΔTP_{inv} = 1.02 (*StdDev* = 0.13).

We also analyzed *display stiffness* (3) x *input mapping* (2) with a repeated measures ANOVA on their Pearson's *r* correlation coefficients. We found a significant main effect of *input mapping* ($F_{1,11}$ = 15.561, $p < 0.05$), with rate control achieving higher correlations to Fitts' law than position control.

Figure 3 shows the best fit lines derived from combining all subjects' data for each condition, provided for visual inspection of the general results. In our above analysis, we used per-participant models because it was previously unknown whether bending a display followed Fitts' law and we wanted to inspect the variation of participants' performance [29]. As a result, these lines do not have a one-to-one correspondence with the parameters presented in Table 1, but are useful for highlighting the overall trends.

Movement Times and Errors

We also performed a repeated measures ANOVA using *display stiffness* (3) x *input mapping* (2) x *index of difficulty* (12) for movement times. The analysis revealed *input mapping* was a significant main effect ($F_{1,11}$ = 241.338, $p < 0.001$), with position control resulting in lower movement times, as well as *index of difficulty* ($F_{1,11}$ = 241.338, $p < 0.001$). We also found that there was a significant interaction effect between *display stiffness and input mapping* ($F_{2,22}$ = 6.755, $p < 0.05$) and between *input mapping* and *index of difficulty* ($F_{11,121}$ = 21.278, $p < 0.001$).

Table 2 shows the error rate for each of the experimental conditions. Overall, the average error rate was 3.8%, very close to the 4% error rate assumed by Fitts' law [4,29].

User Feedback

Many non-parametric tests (e.g., Friedman) are limited in their ability to investigate both repeated measures and factorial designs [30]. To compensate for this, we ran a repeated measures ANOVA on the Aligned Rank Transform [30] of participants' ratings of the three questions. Figures 4-6 compare the mean ratings for each combination of the *display stiffness* and *input mapping* factors.

Regarding the question of whether a condition was *efficient for completing the task*, *input mapping* was found to be a significant factor ($F_{1,11}$ = 29.105, $p < 0.001$). Participants rated the position controlled conditions higher than the rate controlled conditions.

With respect to the question of whether a condition was *comfortable to bend*, the analysis did not reveal any significant factors or interaction effects.

Finally, for whether a condition was *easy to use*, we found that *input mapping* was a significant factor ($F_{1,11}$ = 28.820, $p < 0.001$). With this question, participants also rated the position controlled conditions higher than the rate controlled conditions.

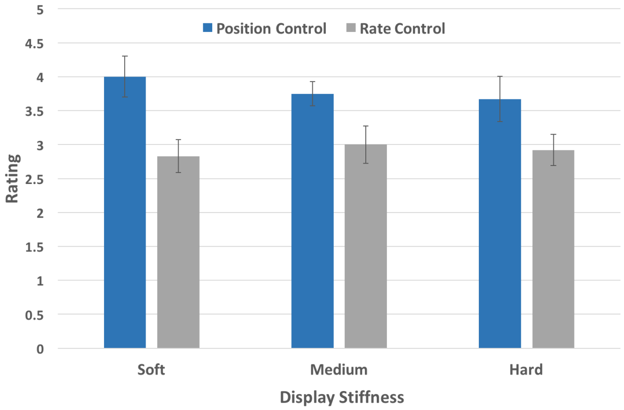

Figure 4. Mean (*s.e.)* user ratings for the question *"I found <this condition> efficient for performing the task"*.

DISCUSSION

Overall, our results showed that bend input for cursor control follows Fitts' law and, for the range tested, display stiffness did not have an effect on performance. At the same time, position controlled navigation was shown to be more efficient and highly preferred compared to rate control.

Input Mapping

As hypothesized, position control had significantly faster movement times than rate control (*H1*), as well as significantly higher throughputs (*H2*). Previous work has shown that position control can facilitate better performance than rate control with bend input and elastic joysticks [1,3,12], and our results align with these observations. The differences between the two input mappings were quite large: across all levels of display stiffness, position control produced throughputs (TP_{avg}) that were 1.62 bits per second higher on average, a 78% improvement.

This bandwidth difference is likely a product of the distinct methods of controlling cursor position. Position control is a *zero-order* transfer function, while rate-control is *first-order* [32]. With position control, users apply a force to move the cursor to a corresponding location on the display; it quickly accelerates the cursor to its maximum velocity. Using rate control, users need to increase force to bring the cursor to its maximum velocity, which naturally has a slower rate of acceleration. The Fitts' law models (Table 1) show that rate control has slightly large, but acceptable, intercepts (*a*), and the difficulty in starting and stopping may be a constant additive factor.

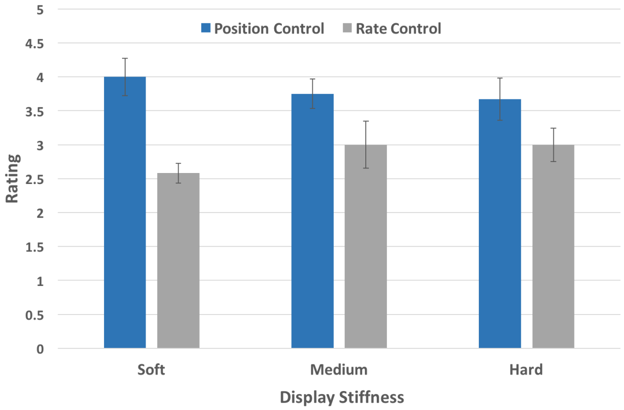

Figure 6. Mean (*s.e.)* user ratings for the question *"I found <this condition> easy to use."*

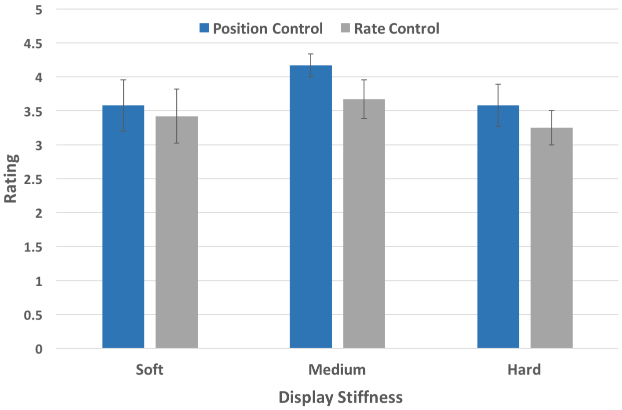

Figure 5. Mean (*s.e.)* user ratings for the question *"I found <this condition> comfortable to bend."*

The questionnaire responses unsurprisingly reflected this large difference in task performance: participants found that position control was both *easier to use* and *more efficient* for the targeting task (Figures 4 and 6). Often they were more straightforward, providing comments such as, *"the direct mapping of bend to location is easier to use"*, "*I have a tendency to overshoot targets* <with rate control>*"*, and *"position control made it easier to hit far targets"*. In one extreme case, a participant remarked, *"I hate rate control."*

We based the rate control algorithm on observations of prior work and our pilot studies, but further refinement is likely necessary to make such a mapping more efficient when bending a display—particularly when compared to position control.

Display Stiffness

We had also hypothesized that the three display stiffness levels would have similar movement times (*H3*) and throughputs (*H3*). As predicted, the analysis did not find any significant main effects for either measure. Although non-significant is not the same as equivalent, the mean throughputs are similar and there are no trends across input mappings that suggest an overall effect.

This result is in line with Kildal and Wilson [15] who did not find any differences between levels of stiffness when they asked participants to maintain a specific level of force. In other words, we found that when the amount of effort required to move the cursor to a specific location or velocity was the same across devices, stiffness did not affect performance.

Previous work proposed that a higher degree of stiffness can be beneficial for rate control (and lower degrees for position control), suggesting that an interaction effect might occur [32]. Although the analysis revealed an interaction effect for movement times, it was not consistent with those prior observations. Given that our levels of stiffness were low, all three may have been in the range more suitable for position control. Looking at the data more closely, we found that the interaction was as a result of the Medium stiffness. Rate control produced consistent movement times across degrees of stiffness, but the Medium device had faster movement times than both the Soft and Hard devices in the position control conditions. One explanation is because the Soft device requires the largest bend and the Hard device placed a lower limit on our maximum required force, the Medium device simply struck a balance between the two and outperformed the others when the cursor was a direct mapping of shape/force. At the same time, this was balanced out by a slightly higher error rate (Table 2).

The analysis of our user feedback did not reveal any differences between stiffness levels either. In this case, however, participants generally had strong opinions but did not agree with each other. Some participants described the Soft device as *"their favorite"* because it *"required the least amount of strain."* Others remarked that *"it felt too flimsy"* or that it was *"uncomfortable and unintuitive."* For the Hard device, one participant reported that it was *"difficult to be accurate"*, but another found it *"easier for targets that are far apart"*. In the middle, the Medium device had more positive opinions, including that *"it more naturally snapped back into position"* and had a *"good balance of rigidity"*. But some others *"did not feel any difference between* <Medium> *and Hard."*

Overall, we can see that the stiffness of a flexible display does not appear to affect targeting efficiency when torque is controlled. As a consequence, developing interactions based on target forces might be more appropriate than requiring specific angles of deformation. Kildal and Wilson established that maintaining torque is consistent across levels of stiffness [15], and our results demonstrate that this is also the case for rapidly targeting to a specific level of torque. Essentially, extremely flexible devices may not be necessary for an efficient user experience. If future designers of flexible smartphones follow this approach, they may be able to engineer a better product: one that balances comfort and robust industrial design, without sacrificing targeting efficiency.

Fitts' Law Correlations

An essential takeaway is that bend input is highly correlated with Fitts' law for one-dimensional movement (Table 1). This is both true for position control (r = ~0.92) and rate control (r = ~0.96). It is interesting to note that we observed appreciably higher correlation coefficients than Ahmaniemi et al. [1] for these two input mappings (r = 0.45 and 0.79, respectively). We suggest that, by more closely following the standards of ISO 9421-9 [11] and Soukoreff and MacKenzie [29], we gained new insights into the Fitts' law performance of bending. This might be attributed to either the presentation of the task or the procedure for data analysis—or both.

At the same time, our correlations are slightly lower than established interaction techniques that 'completely' follow Fitts' law. One factor might be our use of Crossman's adjustment for width [4], which typically lowers correlations but offers more accurate a and b coefficients [33]. On the other hand, some properties of elastic devices might produce lower fits than an isometric or isotonic device. Prior work showed that users have difficulty distinguishing between small differences in applied force [2], particularly when maintaining a specific torque with a highly flexible device [15]. Several participants commented that they found the smallest amplitude difficult, even with the larger target widths. These low *IDs* were corrected to even lower ID_es, yet still generated large than expected movement times—typically not the case [33]. Participants also commented that, when using position control, the smallest target width was more difficult to hit. It is possible that they compensated for these higher *IDs* with additional sub-movements, increasing movement times and further reducing the fit for position control. These observations further support the idea that input mappings must be carefully tuned to be appropriate for the interface [1].

CONCLUSION

In this paper, we presented an experiment to investigate one-dimensional targeting using bend input. Participants completed an ISO 9421-9 Fitts' law experiment using two input mappings, position control and rate control, and three levels of display stiffness. Our results demonstrate that bend input to control a cursor follows Fitts' law, with position control generating significantly higher throughputs than position control. The experiment also revealed that when the required force is held constant, there were no performance differences between levels of device stiffness.

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REFERENCES

1. Teemu T. Ahmaniemi, Johan Kildal, and Merja Haveri. 2014. What is a device bend gesture really good for?. In *Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems* (CHI '14). ACM, New York, NY, USA, 3503-3512.
2. Felipe Bacim, Mike Sinclair, and Hrvoje Benko. 2013. Understanding touch selection accuracy on flat and hemispherical deformable surfaces. In *Proceedings of Graphics Interface 2013* (GI '13). Canadian Information Processing Society, Toronto, Ont., Canada, Canada, 197-204.

3. Jesse Burstyn, Amartya Banerjee, and Roel Vertegaal. 2013. FlexView: An evaluation of depth navigation on deformable mobile devices. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* (TEI '13). ACM, New York, NY, USA, 193-200.
4. E.R.F.W. Crossman. 1957. The speed and accuracy of simple hand movements. In *The Nature and Acquisition of Industrial Skills*, Crossman and Seymour (eds.). Report to the Joint Committee on Individual Efficiency in Industry.
5. Rob Dijkstra, Christopher Perez, and Roel Vertegaal. 2011. Evaluating effects of structural holds on pointing and dragging performance with flexible displays. In *Proceedings of the 29th Annual ACM Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 1293-1302.
6. Paul M. Fitts. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *J. Exp. Psych.*, 67: 103-112.
7. Antonio Gomes and Roel Vertegaal. 2015. PaperFold: Evaluating shape changes for viewport transformations in foldable thin-film display devices. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI '15). ACM, New York, NY, USA, 153-160.
8. Yves Guiard and Michel Beaudouin-Lafon. 2004. Target acquisition in multiscale electronic worlds. *Int. J. Hum.-Comput. Stud.* 61, 6 (December 2004), 875-905.
9. Sidhant Gupta, Tim Campbell, Jeffrey R. Hightower, and Shwetak N. Patel. 2010. SqueezeBlock: Using virtual springs in mobile devices for eyes-free interaction. In *Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology* (UIST '10). ACM, New York, NY, USA, 101-104.
10. David Holman and Roel Vertegaal. 2008. Organic user interfaces: Designing computers in any way, shape, or form. *Commun. ACM* 51, 6 (June 2008), 48-55.
11. ISO. 2000. 9421-9 Ergonomic requirements for office work with visual display terminals (VDTs) - Part 9: Requirements for non-keyboard input devices, *International Organization for Standardization*.
12. Richard J. Jagacinski, Daniel W. Repperger, Martin S. Moran, Sharon L. Ward, and Betty Glass. 1980. Fitts' law and the microstructure of rapid discrete movements. *J. Exp. Psych.* 6, 92: 309-320.
13. Johnan Kildal. 2012. Interacting with deformable user interfaces: Effect of material stiffness and type of deformation gesture. In *Proceedings of the 7th International Conference on Haptic and Audio Interaction Design* (HAID'12), Charlotte Magnusson, Delphine Szymczak, and Stephen Brewster (Eds.). Springer-Verlag, Berlin, Heidelberg, 71-80.
14. Johan Kildal, Andrés Lucero, and Marion Boberg. 2013. Twisting touch: Combining deformation and touch as input within the same interaction cycle on handheld devices. In *Proceedings of the 15th International Conference on Human-Computer Interaction with Mobile Devices and Services* (MobileHCI '13). ACM, New York, NY, USA, 237-246.
15. Johan Kildal and Graham Wilson. 2012. Feeling it: the roles of stiffness, deformation range and feedback in the control of deformable ui. In *Proceedings of the 14th ACM International Conference on Multimodal Interaction* (ICMI '12). ACM, New York, NY, USA, 393-400.
16. Bhoram Lee, Hyunjeong Lee, Soo-Chul Lim, Hyungkew Lee, Seungju Han, and Joonah Park. 2012. Evaluation of human tangential force input performance. In *Proceedings of the 30th Annual ACM Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 3121-3130.
17. Sang-Su Lee, Sohyun Kim, Bopil Jin, Eunji Choi, Boa Kim, Xu Jia, Daeeop Kim, and Kun-pyo Lee. 2010. How users manipulate deformable displays as input devices. In *Proceedings of the 28th Annual ACM Conference on Human Factors in Computing Systems* (CHI '10). ACM, New York, NY, USA, 1647-1656.
18. I. Scott MacKenzie. 1989. A note on the information-theoretic basis for Fitts' law. *J. Motor Behavior*, 21: 232-330.
19. I. Scott MacKenzie. 1995. Movement time prediction in human-computer interfaces. In *Human-computer interaction*, Ronald M. Baecker, Jonathan Grudin, William A. S. Buxton, and Saul Greenberg (Eds.). Morgan Kaufmann Publishers Inc., San Francisco, CA, USA 483-492.
20. Yusuke Nakagawa, Akiya Kamimura, and Yoichiro Kawaguchi. 2012. MimicTile: A variable stiffness deformable user interface for mobile devices. In *Proceedings of the 30th Annual ACM Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 745-748.
21. Omega Engineering. Strain Gages, Accessories and Instrumentation. 2015. Retrieved June 2, 2015 from http://www.omega.ca/section_eng/strain-gages-accessories.html
22. Robert Penner. 2002. Motion, Tweening, and Easing. In *Robert Penner's Programming Macromedia Flash MX*, McGraw-Hill/Osborne, Berkeley, California, USA, 192-240.

23. PJRC. Teensy 3.1. 2015. Retrieved June 2, 2015 from http://www.pjrc.com/teensy/teensy31.html

24. Gonzalo Ramos, Matthew Boulos, and Ravin Balakrishnan. 2004. Pressure widgets. In *Proceedings of the 22nd Annual ACM Conference on Human Factors in Computing Systems* (CHI '04). ACM, New York, NY, USA, 487-494.

25. Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. 2013. Morphees: Toward high "shape resolution" in self-actuated flexible mobile devices. In *Proceedings of the 31st Annual ACM Conference on Human Factors in Computing Systems* (CHI '13). ACM, New York, NY, USA, 593-602.

26. Joseph D. Rutledge and Ted Selker. 1990. Force-to-motion functions for pointing. In *Proceedings of the IFIP TC13 Third Interational Conference on Human-Computer Interaction* (INTERACT '90), Dan Diaper, David J. Gilmore, Gilbert Cockton, and Brian Shackel (Eds.). North-Holland Publishing Co., Amsterdam, The Netherlands, The Netherlands, 701-706.

27. Toshiki Sato, Jefferson Pardomuan, Yasushi Matoba, and Hideki Koike. 2014. ClaytricSurface: An interactive deformable display with dynamic stiffness control. *Computer Graphics and Applications* 34, 3: 59-67.

28. James Scott, Lorna M. Brown, and Mike Molloy. 2009. Mobile device interaction with force sensing. In *Proceedings of the 7th International Conference on Pervasive Computing* (Pervasive '09), Hideyuki Tokuda, Michael Beigl, Adrian Friday, A. J. Brush, and Yoshito Tobe (Eds.). Springer-Verlag, Berlin, Heidelberg, 133-150.

29. R. William Soukoreff and I. Scott MacKenzie. 2004. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. *Int. J. Hum.-Comput. Stud.* 61, 6 (December 2004), 751-789.

30. Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the 29th Annual ACM Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 143-146.

31. Jacob O. Wobbrock, Kristen Shinohara, and Alex Jansen. 2011. The effects of task dimensionality, endpoint deviation, throughput calculation, and experiment design on pointing measures and models. In *Proceedings of the 29th Annual ACM Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 1639-1648.

32. Shumin Zhai. 1995. *Human performance in six degree-of freedom input control*. Ph.D Dissertation. University of Toronto, Toronto, ON.

33. Shumin Zhai, Jing Kong, and Xiangshi Ren. 2004. Speed-accuracy tradeoff in Fitts' law tasks: On the equivalency of actual and nominal pointing precision. *Int. J. Hum.-Comput. Stud.* 61, 6 (December 2004), 823-856.