ReFlex: A Flexible Smartphone with Active Haptic Feedback for Bend Input

Paul Strohmeier[1,2], Jesse Burstyn[1], Juan Pablo Carrascal[1], Vincent Levesque[3], Roel Vertegaal[1]
[1]Human Media Lab, Queen's University, Kingston, ON, Canada
[2]Department of Computer Science, University of Copenhagen, Denmark
[3]Immersion Canada Corp., Montréal, QC, Canada
[1]{paul, jesse, jp, roel}@cs.queensu.ca, [3]vlevesque@immersion.com

ABSTRACT
ReFlex is a flexible smartphone with bend input and active haptic feedback. ReFlex's features allow the introduction of sensations such as friction or resistance. We report results from an experiment using ReFlex in a targeting task, as well as initial users' reactions to the prototype. We explore both absolute and relative tactile haptic feedback, paired with two types of bend input mappings: position-control and rate-control. We observed that position-controlled cursors paired well with relative bend feedback, while rate-controlled cursors paired well with absolute bend feedback to indicate targets. We also explored an eyes-free condition. Results suggest that while eyes-free, haptic feedback conditions were more error-prone than visual-only conditions, the size of the error was relatively small, and users were able to complete the task in all cases. We present two application scenarios that take advantage of the unique input and output modalities of ReFlex and discuss its potential for within document navigation.

Author Keywords
Flexible Displays; Bend Input; Haptic Feedback; Organic User Interfaces

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

INTRODUCTION
When presented with a tool or a device, we assess its features and attributes to understand what we can do with it, i.e, its perceived affordances [18]. Visual inspection alone cannot convey all of this information and it is often necessary to feel objects with our hands to gain a fuller understanding of its material and structural properties. We perceive these qualities both through tactile stimulation on our skin and kinesthetic receptors in our hands. When an object is deformed, a rich set of sensations come into play to inform us about its internal structure. For example, when reading a paper document, the physical structure of pages can help guide users to particular locations in the document. A book can have physical tabs to indicate chapters and its pages might have dog ears to denote bookmarks or creases at frequently read passages. The distribution of pages between the hands provides some haptic representation of the current reading location. And pages sliding between a user's fingers provide feedback on the speed with which she is navigating. Many, if not all, of these haptic affordances are lost when navigating documents on rigid Tablet PCs. When designing flexible organic user interfaces [9], the structural qualities of the device are inherited from the material of the substrate used in its construction. While haptic technologies have been used to mimic textures of different materials [2], these technologies often focus on surface features. An alternative approach is to modify the perceived material properties of the device [10,25].

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Figure 1. ReFlex, a flexible haptic smartphone.

Reflex: A Haptic Flexible Smartphone
Contributing to the latter approach, we created ReFlex, a flexible smartphone featuring a high-resolution flexible display and a haptic actuator (Figure 1). ReFlex modifies the experience of dry friction when bending the device, as perceived through tactile and kinesthetic receptors of the fingers. This feedback creates possibilities for new interactive experiences, such as simulating the elastic and material sensations that occur while navigating a paper book. We report on results from a study that explores bending using position control and rate control in combination with different types of haptic feedback in a target acquisition task. We found that position control resulted in faster times and higher accuracy than rate control. Participants preferred

relative haptic feedback with position control and absolute haptic feedback with rate control. Following these results, we performed a study evaluating the effectiveness of the haptic rendering techniques for acquiring a target in the absence visual feedback. We found that it was possible to accomplish the task with a relatively low error rate. Based on user observations of the two studies, we discuss the possibilities of our haptic rendering techniques to enhance navigation for long digital documents, providing some of the same qualities as paper books. We present two application scenarios that may improve the browsing experience of lists and documents on flexible smartphones.

RELATED WORK

Elastic Input Devices

Zhai [26] distinguishes between two types of devices: isometric and isotonic. While their suitability for different types of cursor control has been extensively studied, their defining feature is their *stiffness*, i.e. how much they oppose physical displacement. Isotonic devices, e.g., a mouse, have a constant low resistance and are freely moved. Isometric devices, such as, e.g., the IBM TrackPoint [21], fully resist displacement and operate through forces applied. Between them, however, is a third category: that of *Elastic* devices. These have a stiffness, k, has a resistance that is proportional to its displacement. Elastic devices signal their displacement through passive force feedback, and, like springs, are naturally self-centering. Many flexible display devices fit into this category since when deformed, they flex and return to their original state upon release.

Changing an elastic device's stiffness moves it along the isometric-isotonic spectrum. Higher amounts of resistance can afford better rate control, while lower resistance affords more proprioceptive feedback during displacement and can be more suitable for position control [26].

Bendable Devices

Flexible display interactions is a relatively recent, but increasingly popular, field of study. Early explorations, such as Gummi [22], predate the actual use of flexible displays. Some of the first explorations using real flexible displays include Lahey et al.'s PaperPhone [14] and Nokia's Kinetic [11]. Along with these prototypes, there have been several studies of how users perceive the physical properties of deformable devices. Nakagawa et al. [17] presented MimicTile, a bendable device with dynamical stiffness. They demonstrated that participants could accurately identify different levels of stiffness and Kildal et al. [12] reported that users preferred flexible devices that are less stiff than others.

Haptics and Perception

There are many studies on how people use haptic cues to infer an object's properties; most are well beyond the scope of this paper. For example, tactile and kinesthetic cues can be used to create an illusion of texture. Klatzky et al. [13] outline models for a force feedback mouse that simulated varying levels of surface roughness. With TeslaTouch, Bau et al. [2] use electro-vibration to create dynamic friction on a touch surface. Lederman and Jones [15] present a literature survey on how manipulating sensory cues can create both kinesthetic and tactile illusions. Changing visual [23] or auditory cues [3] can create false perceptions of an object's stiffness, while changing an objects configuration can create varying perception of its weight [8]. Conversely, changing the haptic sensory cues can also change the perception of material stiffness [25].

Haptics and Performance

Researchers have found that haptic and tactile feedback can benefit pointing tasks when used to provide direct information about the target. In a Fitts' law targeting task, Akamatsu et al. [1] found that tactile feedback provided on the target resulted in equivalent movement times, but shorter final positioning times, than visual or audio feedback. Forlines et al. [5] reported that haptic signals on targets are beneficial for both crossing and pointing Fitts' law tasks. On the other hand, Kildal et al. [12] demonstrated that passive haptic feedback, in the form of device stiffness, had little to no effect on task performance, but greatly influenced user comfort and feedback on bend interaction.

DESIGN RATIONALE

We were interested in exploring the interaction between bend input with passive force feedback and actuated vibro-tactile feedback. Specifically, we wanted to understand what it means to combine variations of haptic feedback with different styles of bend interaction.

Passive Haptic Feedback

When using a touch screen, kinesthetic feedback provided by the configuration of the arm is largely independent of touch location. Compared to such traditional touch interaction, the ReFlex's passive force feedback provides a strong coupling of proprioceptive feedback with bend input: ReFlex provides a linear correspondence between the applied force and position or speed of a cursor.

Adding Active Haptics to a Bendable Smartphone

We facilitate multisensory feedback and explore the interplay between visual, tactile and kinesthetic experiences. To accomplish this, we augmented the flexible display with a haptic actuator that provides active feedback in addition to the passive elastic forces generated by the device when bent. This enables us to actively modulate the experience of passive haptic feedback experienced by bending the device, generating variations in the perceived elasticity and internal structure.

IMPLEMENTATION

ReFlex is a flexible smartphone prototype with a bend sensor and haptic actuator (Figure 1). Our prototype can be used as a stand-alone device and runs Android 4.2 (Figure 2)

Display

Reflex uses a FOLED display manufactured by LG Display. The 6.0" (135 mm x 77 mm) FOLED display has a resolution of 1280 x 720 pixels and a refresh rate of 60 Hz. The display is mounted on a flexible substrate that extends 5 cm to left

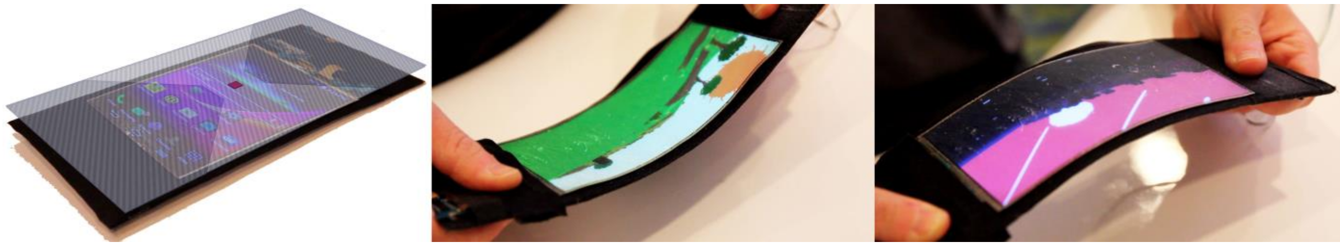

Figure 2. Left: Prototype with internal structure: Dark gray areas are semi-rigid, light gray areas are flexible. Position and size of strain sensor is indicated by the red square. Middle, Right: ReFlex bending in both directions.

and right. This allows for a comfortable grip without occluding the display, and a location for rigid electronics, such as the processor and display driver board.

Rigidity

The structural substrate of the device is designed so that it is most flexible at its center, tapering off towards the semi-rigid ends. This was accomplished by adding trapezoidal re-enforcements on both ends of the device (Figure 2, left).

Input

ReFlex measures the direction and extent of a bend with an Omega Engineering strain gauge [20] placed at its center. A Teensy 3.1 microcontroller samples this strain gauge at 12 bits and ~2000 times per second. The high temporal and spatial resolution of this strain gauge allows us to synchronize the haptic actuation with the passive haptics that are naturally present when bending the device. ReFlex also has a multi-touch sensor which we use for setting up the experiments, and a button on the back, which participants use during the experiment.

Haptic Output

Active haptic feedback is generated using a Tactile Labs Haptuator [24] mounted on the back of ReFlex, parallel to the length of the display. ReFlex uses a vibrotactile transducer, rather than a vibrational motor, for precise temporal control of haptic signals. The Haptuator generates precise discrete pulses at an acceleration of up to 73 m/s^2 and at rates up to 1000 Hz [24]. Discrete pulses are inaudible, and a continuous series of pulses are audible only above ~500 Hz. The Haptuator is meant to be driven by a standard audio amplifier. For our study, it was driven by the sound card of the computer running the experimental software.

Software

A C++ program polls the Teensy microcontroller for sensor values and converts them into cursor movement 200 times per second. It then passes these values to a Max patch that generates audio signals for the Haptuator. ReFlex runs a simple Android client application that receives cursor and target information from the computer over WiFi to draw them on the display. ReFlex is tethered to optimize the synchronizations between haptic and visual feedback, however it can also be used as a stand-alone, wireless device.

BEND INPUT MAPPINGS

ReFlex uses two different types of cursor control, following the definitions put forward by Zhai [26]:

Position Control (PC)

For ReFlex, position control means that sensor values are directly mapped to pixels on the display's x-axis, i.e., the cursor position (p_c) is linearly proportional to the amount of bend (x) applied to the device:

$$p_c(x) = x$$

When the device is flat, the cursor is in the center of the display. The cursor is at the left extremity of the display when ReFlex is fully convex, and on the right extremity when ReFlex is fully concave. This mapping creates a linear correspondence between passive kinesthetic feedback and the visual position of the cursor on the display.

Rate Control (RC)

With rate control, the user controls position of the cursor by manipulating its speed and direction via bend gestures. The direction of movement is same as in Position Control. The speed at which the cursor moves (r_c) is mapped to the extent of the bend with the following sinusoidal easing function:

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

HAPTIC FEEDBACK ALGORITHMS

Active tactile haptic feedback was created using an audio signal consisting of a train of discrete pulses. We applied a high-pass filter (at 80Hz) to the signal to remove any low frequency elements, helping each pulse to become more distinct. A low-pass filter (at 200 Hz) helped to attenuate the audibility of the signal.

We also modulated the amplitude of the signal so the haptic pulses would be felt stronger at the extremes of bend input (~160db) and weaker when the device is close to rest (~110db). This increased the perceived strain proportionally to the how much the device is bent.

We used two types of bend input to haptic feedback mappings, as explained next. Depending on the mapping, we could create the haptic illusion of altered material properties, similar to 3D-press [10].

Haptic Feedback Mapping Types

Absolute Bend Feedback (A): in this mapping, the rate of the pulse train (r_p) varies linearly with the extent of bend (x). The more extreme the bend, the higher the pulse train rate:

$$r_p(x) = x$$

The duty cycle of the pulse train is 50% for all rates. When combining this mapping with a cursor rate cursor (A-RC), the pulse rate varies with the speed of the cursor. This created the feeling that fixed locations on the display trigger haptic pulses when the cursor passes over them. On the other hand, when combining this mapping with cursor position control (A-PC), the synchronization between cursor location and haptic pulses is lost. The device simply pulses faster the further it is bent.

Relative Bend Feedback (R): for this mapping, the pulse train is not necessarily periodic. Instead, its rate varies linearly with the *speed* of the bend movement, i.e., the bend velocity:

$$r_p(x) = \frac{\Delta x}{\Delta t}$$

Each single pulse of the train is a 1ms length square pulse. When combining this mapping with cursor position control (R-PC), absolute locations on the display seem to trigger haptic pulses as the cursor passes over them. Conversely, when using rate control (R-RC), the pulse rate seems to be synchronized with the acceleration of the cursor.

Task

Participants performed a subset of a one-dimensional Fitts' law targeting task. Two vertical ribbons appeared on the display, with varying center-to-center distances. Target width was held constant at 80 pixels. Users were asked to alternately click within the left and right ribbon 25 times. Each block of trials began after the participant placed the cursor within the left target and pressed the button. Participants were instructed to perform the task as quickly and as accurately as possible.

Experiment Design

We used a 3x2x3 factorial within-subject design with repeated measures. Our factors were haptic feedback (3 levels, discussed below), cursor control (position control and rate control), and target distance (150, 500, 960 pixels). Participants performed one block of 25 trials for each of the 18 combinations of factors. Condition order was counterbalanced between participants. Participants practiced with each combination of haptic feedback and cursor control until they achieved less than 10% improvement between trials. Our measures were targeting time and error rates.

Haptic Feedback

Participants were provided with 3 levels of haptic feedback: no feedback, absolute bend feedback, and relative bend feedback. Depending on the cursor control, the active feedback provided information on cursor position (A-PC), cursor speed (R-PC, A-RC), or cursor acceleration (R-RC).

Participants

12 participants performed this experiment (7 male, 5 female) with ages ranging from 20 to 38 years. Most participants (10/12) were right handed.

EXPERIMENT 1 RESULTS

We analyzed targeting times using a repeated measured ANOVA on *haptic feedback* (3) x *cursor control* (2) x *target distance* (3). The analysis showed that *cursor control* was a significant factor ($F_{1,11}$=251.02, $p < 0.001$), with position control resulting in faster targeting times than rate control. We also found that *target distance* was a significant factor ($F_{2,22}$=339.01, $p < 0.001$) and there was a significant interaction between *cursor control* and *target distance* ($F_{2,22}$=108.40, $p < 0.001$). We found no significant effects of either type of *haptic feedback*.

We analyzed the errors using a repeated measured ANOVA on haptic feedback (3) x cursor control (2) x target distance (3). The analysis showed that cursor control was a significant factor ($F_{1,18}$=9.86, $p < 0.05$), with position control resulting in fewer errors than rate control. We also found that there was a significant interaction effect between cursor control and target distance ($F_{2,36}$=0.74, $p < 0.05$).

EXPERIMENT 1 DISCUSSION

Rate Control vs. Position Control

Users were able to complete the task faster using position control than using rate control. When first comparing rate control to position control most users also commented that they did not like rate control. After using the rate controlled input for a longer period of time, however, participants commented they also found rate control easy to use. Some users stated that rate control was preferable for targets at large distances, while position control was better for targets at short distances. This was, however, not supported by the targeting times; in fact, the interaction effect we observed indicates the opposite. The error rates appeared constant for all target distances in rate control, while for position control larger target distances caused more errors. This may in part explain participants' experiences: while position control is both faster and more precise, the precision benefit over rate control is greatest for short movements.

Haptic Rendering

We did not find any measurable effects of the different types of haptic feedback on task completion times. Interestingly, this contradicts the feedback comments we obtained from participants: many of them found the haptic feedback helpful. This result does not contradict previous research that observed effects of haptic feedback on pointing tasks only when direct information about the target is signaled (e.g. crossing the center or edge) [1,5], as in our experiment we only provided indirect target information such as speed and position.

We examined participants' comments to understand how the haptic feedback might have influenced their opinion on the prototype. P2 stated that *"if I specifically pay attention to the feedback, it is helpful, [but I think] my brain responds faster to my eyes than to my finger"*, suggesting dominance of the visual system in the task [1]. P6 commented that *"the haptic feedback is helpful; it allows me to focus less on the visuals."* We found this comment interesting given the measured results; despite the fact there were no differences in performance, the participants felt it was the case. It is possible that the haptic feedback can generate an additional perceptual illusion, in the same vein to perception of animation speed in moving progress bars [7].

Combinations of Haptic Feedback and Cursor Control

The two different types of cursor control types and methods of generating haptic feedback can be combined in four unique ways. Each combination results in a very different experience for the user:

Relative Bend Feedback, Position-Controlled Cursor (R-PC)

Here, as the cursor moves across the screen, the user receives pulses of haptic feedback when crossing fixed locations on the screen. When the device is released, the cursor self-centers as a result of the elasticity of the device and position control. The haptic pulses become stronger towards the edge of the device; the active haptics correlate with the user's perception of passive bend forces. These properties seem to make this combination one of the easiest to interpret. For instance, P1 stated "*I can almost close my eyes and roughly have an idea of where the cursor is*", an idea that we explored further in Experiment 2. The synchronization of feedback with body and display shape makes this haptic configuration unlike regular vibration. Instead, it is experienced as friction within the device, creating rich haptic images. Participants explained it in diverse ways: "*It almost feels lit it's more fibrous*" (P1), "*It feels like I'm bending a twig of wood*" (P3), "*It's a little bit like when you are moving a rubber band along a smooth surface*" (P4).

Absolute Bend Feedback, Position-Controlled Cursor (A-PC)

Here, the cursor behaves the same way as for the previous combination, however, the pulses are no longer synchronized to specific locations. Instead, the further the display is bent, the faster the pulse rate. This gave an experience somewhat reminiscent of flicking pages of a book at a rate that corresponds to the exerted force. P4 explains it is "*because when you bend it and hold statically the vibrations just continue at a steady pace*", while P3 states "*that's not a trait I would attribute to an inanimate type of object that I am working with*". While the mapping is not direct, participants did experience this combination potentially useful. P6 considered that "*it does a very good job in providing the user with some sort of feedback as to the amount of pressure to exert on the screen*", while P5 considered it to be "*consistent throughout*", and P3 suggested that this combination "*could be something very useful in gaming.*"

Absolute Bend Feedback, Rate-Controlled Cursor (A-RC)

In this cursor control, the amount and direction of bend determines the speed and direction of the cursor. The haptic pulses appear at regular intervals which become shorter the further the device is bent. This provides an effect of the pulses being triggered by the cursor moving over fixed locations on the display; the haptic pulses are experienced as the texture of the surface the cursor is passing over, or as explained by P1, "*It feels like it's bumping a regular number of times as it moves across the distance (…) It's like a texture, like a gradient*". This combination of cursor control and feedback style was experienced as intuitive. "*The haptic feedback just makes me more aware of the speed of the cursor*" (P3); "*It helps me know when to stop moving the cursor or when to slow it down*" (P4).

Relative Bend Feedback, Rate-Controlled Cursor (R-RC)

With this cursor control, the feedback has haptic pulses triggered with changes in cursor speed. It appeared difficult to interpret and makes the interaction feel disjoint: "*I'm not entire sure of what the haptic feedback is indicating*" (P3); "*It doesn't particularly feel like the feedback is helping me*" (P4); "*[the task with this haptic feedback is] not necessarily easier, it supplements but doesn't make it easier*" (P5). P1 and P6 suggested, "*I don't like this*".

With combinations R-PC and A-RC, the cursor movement and active haptic output appear closely synced, leading to a predictable behavior of the haptic qualities of the device. For combination R-PC, it is experienced like the internal structure of the device is changing, while A-RC is experienced much like modulating surface textures that the cursor moves over. While A-PC did not have these properties, its clear mapping was still considered useful. R-RC did not have the same type of coupling experienced with R-PC and A-RC, nor did it have a clear mapping, like combination A-PC. Unlike all other combinations, participants did not enjoy it. With these results in mind, we used the optimal combinations to test if the prototype would allow a user to perform a task in an eyes-free scenario.

EXPERIMENT 2

We conducted a second experiment to assess the effects of haptic feedback for indicating targets without visuals. Participants performed the same targeting task as in Experiment 1, with the same apparatus but a somewhat larger target width of 120 pixels. We encouraged the participants to prioritize accuracy over speed.

Haptic Feedback

The participants used haptic feedback to find the target. In one condition, haptic feedback only occurred when the cursor was over the target. In another, the haptic feedback was removed only when the cursor was over the target. A distinction from other investigations that utilize haptic feedback to signify targets [1,5] is that our feedback is based both on the presence of a target, as well as the behavior of the cursor. That is, in both haptic conditions, the user only feels haptic feedback when the cursor is moving. We chose the feedback types that participants felt closely matched cursor control: we used relative bend feedback with a position-controlled cursor (R-PC) and absolute bend feedback combined with the rate-controlled cursor (A-RC).

Experiment Design

We used a 3x2x2 factorial within-subjects design with repeated measures. Our factors were *feedback method* (visual feedback, haptics present only when on target, and haptics always present except when on target), *cursor control*

		Cursor	
		Position Control	Rate Control
Feedback Type	Visual-only	1.00 *(.95)*	1.00 *(0.95)*
	Haptics On Target	4.17 *(6.32)*	11.00 *(8.38)*
	Haptics Off Target	3.17 *(4.71)*	5.00 *(2.95)*

Table 1. Mean number of errors in Experiment 2.

		Cursor	
		Position Control	Rate Control
Feedback Type	Visual-only	11.09 *(5.33)*	10.90 *(10.51)*
	Haptics On Target	23.15 *(17.6)*	60.03 *(39.69)*
	Haptics Off Target	22.94 *(23.99)*	31.91 *(28.74)*

Table 2. Mean error distance (pixels) in Experiment 2.

(position control and rate control), and *target distance* (500 and 960 pixels). Our dependent measures were number of errors and error size.

Participants and Training

6 participants performed this experiment (4 male, 2 female), with ages between 20-26. Most (5/6) were right handed. They were given 90 seconds to explore each combination of haptic rendering.

EXPERIMENT 2 RESULTS

We analyzed errors using a repeated measured ANOVA on *feedback method* (3) x *cursor control* (2) x *target distance* (2). The analysis showed that *feedback method* had a significant effect ($F_{2,10}$=7.20, $p < 0.05$) on the number of errors. Post-hoc tests, with Bonferroni corrected comparisons, revealed that visual feedback had significantly fewer errors than the condition where haptic texture was removed from the targets. There were no significant effects of either cursor control or target distance on error rates. Table 1 outlines the mean number of errors for each combination of feedback method and cursor control. Table 2 presents the mean error distances.

EXPERIMENT 2 DISCUSSION

Unsurprisingly, the error rate and average error distance were higher in the eyes-free conditions. However, participants were able to complete this experiment without visuals in both cursor control conditions. The largest average error size was around 60 pixels (~7 mm), the smallest average error size was less than 25 pixels (~2.5 mm) from the target.

Participants were split between their preference of haptics on targets vs. haptics off targets. Some preferred the haptics on target condition, because it felt as though they were notified once they reached the target. Others preferred the haptics off targets, as they felt it was more continuous. Transitioning from the in-between space to the targets during the haptics off target condition was described as an interesting sensation. Participants used colorful descriptions in trying to capture this experience. P2 stated that it was as though *"the space between the targets is land and the haptic feedback is water. It's like falling into water"*. Other descriptions used were *"It's like sand and ice"*. Often, haptic feedback areas were referred to as "*coarse"*, and the blank ones as "*smooth."*

AFFORDANCES OF REFLEX

The rich metaphors expressed by the participants indicate that ReFlex is capable of eliciting haptic sensations beyond what we would expect of traditional vibro-tactile feedback. The interplay between the passive force feedback and active tactile feedback of the device provides perceived physical affordances that can be controlled to match the requirements of the task at hand. These affordances can emulate mechanisms that we are familiar with from the physical world. For example, in the same way as we assess the length of a book by bending it and flipping through its pages, a shorter digital document would generate less haptic pulses when the device is bent than a longer one. Frequency of pulses would simulate page-flipping speed. These methods can also provide implicit information of one's usage history: just as a physical book tends to open to a section that a reader has studied intently, we could gently guide a user to the most visited sections in a digital document by varying the perceived separation between pages—i.e., the consecutive haptic pulses. We believe that the haptic feedback methods we demonstrated are suitable for providing a user with haptic renderings of content, inspired by the physical affordances and wear and tear of physical media.

Haptic Qualities for Reading

Improving the affordances of digital documents to better facilitate within-document navigation is of increasing importance, as people use more digital devices such as the iPad or Kindle to consuming magazines and books. While using these devices for accessing digital documents has numerous advantages, there are downsides to not using paper in reading tasks. These are discussed in O'Hara and Sellen's widely cited work comparing paper documents with their digital counterparts [19], as well as in Marshall and Bly's report on navigation in paper documents [16]. A critical message from these works is that the haptic affordances of paper provide users with serendipitous within-document navigation methods that are lost in reading digital documents. Previous research has proposed several ways to emulate the physical affordances of paper. Some examples include the dual slate reader presented by Chen et al. [4] and Girouard et al.'s DisplayStacks [6], based on multiple thin-film displays, among others. Our findings suggest that flexible devices that combine active and passive haptic feedback may provide an interesting approach to improving within-document navigation for digital documents. The affordances of ReFlex can be used to support the types of serendipitous navigation that we are accustomed to from paper documents, in a form suitable for digital content.

SAMPLE APPLICATIONS

Based on these thoughts, we created two applications that take advantage of active and passive haptic feedback to support within document navigation. Like our experiments, these applications use the button on the back of the device.

Figure 3. Left: Using A-RC for off-screen browsing of large lists, and combination R-PC for selecting on-screen items in the list. Right: Using R-PC for scrolling a text, and A-RC for annotating items.

Large List Navigation

Rate control and position control can act synergistically for bend based input. Precise on-screen targeting actions can use a position-controlled cursor, while off-screen actions that require fast motion or continuous input, such as scrolling, are better suited for rate control [26]. A scenario that takes advantage of this technique is navigation through large lists. Figure 3 (left) shows a user navigating a large list with bending gestures, using rate control for off-screen list browsing and position control when selecting on-screen items from the list. Users can select rate control by pressing and holding the back-of-the-device button during bends. When the button is released, ReFlex uses position control. Items are selected from the list with a click of the button in both cases. The haptic feedback switches between absolute and relative such that pulses always occur at the transition between items on the list. For item selection (R-PC) these are experienced as physical obstacles the cursor moves over, and for off-screen scrolling (A-RC) users experience obstacles as items enter the display.

Text Navigation and Annotation

Our second application is inspired by the wear and tear of physical documents that occurs while reading. Figure 3 (right) shows our e-reader application, which features a highlight function. Users scroll through off-screen content using rate control. Bending ReFlex into a concave shape moves the text up; the opposite moves the text down. When the user clicks the button, the application switches from reading mode to highlight mode. When in this mode, users can use position control to highlight lines of text. Highlighted areas are identifiable in two ways: visually via a brighter foreground color, as well as haptically through a texture. When scrolling, a highlighted area entering the viewport is experienced as having more friction than its surrounding text. As a user scrolls, this change in texture allows them to feel that they are passing a highlighted section – even when not attending visually or when scrolling quickly. The additional friction invites the user to pause at a previously highlighted section, like a dog ear invites the reader to open the book to a previously highlighted page.

LIMITATIONS

The preliminary evaluation presented in this paper was intended as a starting point for a more thorough study of the perceived material properties of bendable devices when augmented with haptic rendering. We obtained significant results for some variables from our experiments, but our sample size was small. We therefore do not consider it a fully conclusive or exhaustive experimental study. Our users' feedback was, however, informative and valuable.

CONCLUSION & FUTURE WORK

We presented ReFlex, a flexible smartphone with passive and active haptic feedback. The evaluation of the prototype indicates that it has potential for enhancing document browsing tasks. We discussed this possibility and we presented two application scenarios, one for browsing long lists and another for text navigation and annotation.

Many open questions remain, and we hope to address them in future work. The combination of bending, active haptic feedback, and different input-to-cursor mappings allowed us to create an extremely expressive device. By modulating several parameters of the haptic pulses—such as rate, amplitude and filtering—, a rich haptic design language can be developed, one that could be used to incorporate sensations of material and structure in interface design. Further investigation is needed to empirically determine the suitability of this language for enhancing applications such as browsing digital documents.

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REFERENCES

1. Motoyuki Akamatsu, I. Scott MacKenzie, and Thierry Hasbrouc. 1995. A comparison of tactile, auditory, and visual feedback in a pointing task using a mouse-type device. *Ergonomics* 38: 816-827.
2. Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison. 2010. TeslaTouch: electrovibration for touch surfaces. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology* (UIST '10). ACM, New York, NY, USA, 283-292.
3. Frank Biocca, Jin Kim, and Yung Choi. 2011. Visual Touch in Virtual Environments: An Exploratory Study of Presence, Multi-Modal Interfaces, and Cross-Modal Sensory Illusions. *Presence*, 10: 247-265.
4. Nicholas Chen, Francois Guimbretiere, Morgan Dixon, Cassandra Lewis, and Maneesh Agrawala. 2008. Navigation techniques for dual-display e-book readers. In *Proceedings of the SIGCHI Conference on Human*

Factors in Computing Systems (CHI '08). ACM, New York, NY, USA, 1779-1788.

5. Clifton Forlines and Ravin Balakrishnan. 2008. Evaluating tactile feedback and direct vs. indirect stylus input in pointing and crossing selection tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '08). ACM, New York, NY, USA, 1563-1572.
6. Audrey Girouard, Aneesh Tarun, and Roel Vertegaal. 2012. DisplayStacks: interaction techniques for stacks of flexible thin-film displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 2431-2440.
7. Chris Harrison, Zhiquan Yeo, and Scott E. Hudson. 2010. Faster progress bars: manipulating perceived duration with visual augmentations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10). ACM, New York, NY, USA, 1545-1548.
8. Masaharu Hirose, Karin Iwazaki, Kozue Nojiri, Minato Takeda, Yuta Sugiura, and Masahiko Inami. 2015. Gravitamine spice: a system that changes the perception of eating through virtual weight sensation. In Proceedings of the 6th Augmented Human International Conference (AH '15). ACM, New York, NY, USA, 33-40.
9. 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.
10. Johan Kildal. 2010. 3D-press: haptic illusion of compliance when pressing on a rigid surface. In *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction* (ICMI-MLMI '10). ACM, New York, NY, USA, Article 21, 8 pages.
11. Johan Kildal, Susanna Paasovaara, and Viljakaisa Aaltonen. 2012. Kinetic device: designing interactions with a deformable mobile interface. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '12). ACM, New York, NY, USA, 1871-1876.
12. 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.
13. Roberta L. Klatzky and Susan J. Lederman. 2006. The perceived roughness of resistive virtual textures: I. rendering by a force-feedback mouse. *ACM Trans. Appl. Percept*. 3, 1 (January 2006), 1-14.
14. Byron Lahey, Audrey Girouard, Winslow Burleson, and Roel Vertegaal. 2011. PaperPhone: understanding the use of bend gestures in mobile devices with flexible electronic paper displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11). ACM, New York, NY, USA, 1303-1312.
15. Susan J. Lederman and Lynette A. Jones. 2011. Tactile and Haptic Illusions. *IEEE Transactions on Haptics* 4, 4: 273-294.
16. Catherine C. Marshall and Sara Bly. 2005. Turning the page on navigation. In *Proceedings of the 5th ACM/IEEE-CS joint conference on Digital libraries* (JCDL '05). ACM, New York, NY, USA, 225-234.
17. Yusuke Nakagawa, Akiya Kamimura, and Yoichiro Kawaguchi. 2012. MimicTile: a variable stiffness deformable user interface for mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, 745-748.
18. Donald Norman. 1988. *The Psychology of Everyday Things*. Basic Books.
19. Kenton O'Hara and Abigail Sellen. 1997. A comparison of reading paper and on-line documents. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems* (CHI '97). ACM, New York, NY, USA, 335-342.
20. Omega Engineering. Strain Gages. 2015. http://www.omega.ca/guides/straingages.html
21. Joseph D. Rutledge and Ted Selker. 1990. Force-to-motion functions for pointing. In *Proceedings of the IFIP TC13 Third International 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.
22. Carsten Schwesig, Ivan Poupyrev, and Eijiro Mori. 2004. Gummi: a bendable computer. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '04). ACM, New York, NY, USA, 263-270.
23. M.A. Srinivasan, G.L. Beauregard, and D.L. Brock. The Impact of Visual Information on the Haptic Perception of Stiffness in Virtual Environments. In *Proceedings of ASME Dynamic Systems and Control Division (1996)*, 58. 555-559.
24. Tactile Labs. Hapuator Mark II. 2012. http://www.tactilelabs.com/products/haptics/haptuator-mark-ii-v2/
25. Hsin-yun Yao and Vincent Hayward. 2006. An experiment on length perception with a virtual rolling stone. In *Proceedings of EuroHaptics 2006*. Springer-Verlag, 325-330.
26. Shumin Zhai. 1995. *Human Performance in Six Degree of Freedom Input Control*. Ph.D Dissertation. University of Toronto, Toronto, ON.