FlexStylus: Leveraging Bend Input for Pen Interaction

Nicholas Fellion
Carleton University
Ottawa, Canada
nicholas.fellion@carleton.ca

Thomas Pietrzak
University of Lille
Villeneuve d'Ascq, France
thomas.pietrzak@univ-lille1.fr

Audrey Girouard
Carleton University
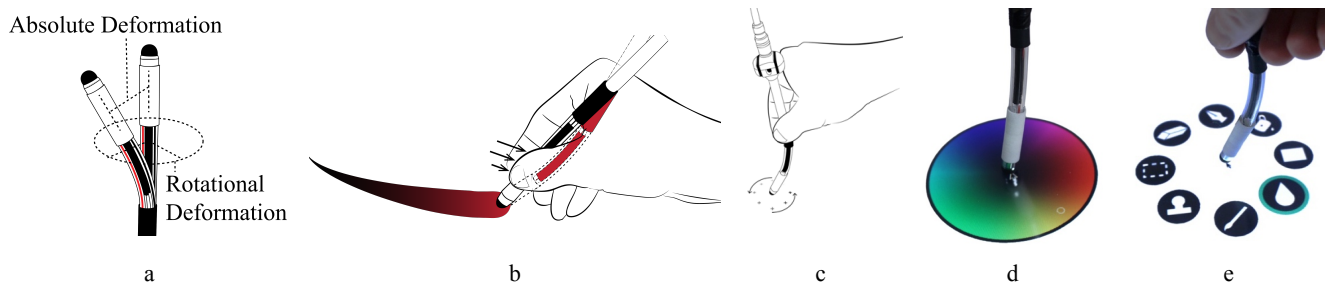Ottawa, Canada
audrey.girouard@carleton.ca

Figure 1: We measure absolute and rotational deformation (a). Examples of interaction techniques leveraging bending input: (b) controlling stroke width, (c) performing circle gesture, (d) using color-picker, (e) using a radial menu.

ABSTRACT

FlexStylus, a flexible stylus, detects deformation of the barrel as a vector with both a rotational and an absolute value, providing two degrees of freedom with the goal of improving the expressivity of digital art using a stylus device. We outline the construction of the prototype and the principles behind the sensing method, which uses a cluster of four fibre-optic based deformation sensors. We propose interaction techniques using the FlexStylus to improve menu navigation and tool selection. Finally, we describe a study comparing users' ability to match a changing target value using a commercial pressure stylus and the FlexStylus' absolute deformation. When using the FlexStylus, users had a significantly higher accuracy overall. This suggests that deformation may be a useful input method for future work considering stylus augmentation.

Author Keywords

Pen interaction; input technique; bending; deformation; augmented stylus; HCI

ACM Classification Keywords

H.5.2 User Interfaces, Input devices and strategies (e.g., mouse, touchscreen)

INTRODUCTION

For artists, digital media offers some advantages over physical media, such as non-destructive editing, automation, and potential novel effects. However, conveying artistic intent to a computer system can be problematic. An artist working in traditional media, such as a painter or pastellist, can subtly manipulate their artistic tool to create different effects, while a digital artist working with a non-augmented stylus is only able to indicate a path, shape, or point on the surface of the tablet. Augmented styluses help solve this problem by using physical inputs such as pressure or tilt to function as parametric controls [12]. Current augmented styluses still fall short of emulating traditional media; their rigid construction means that they do not provide the continuous haptic feedback of, for example, the bristles of a brush on a page.

With the FlexStylus, we introduce another type of augmentation: bending. By bending the device, users can manipulate artistic parameters such as brush width (Figure 1b). The FlexStylus uses a cluster of four fibre optic deformation-detecting sensors to determine the rotational angle, as well as the degree of absolute bending applied to the device (Figure 1a). The FlexStylus is not designed to replicate a particular traditional artistic tool. Instead, it is an input device designed to take advantage of types of hand movements previously unexplored in the domain of stylus devices.

Following a review of relevant prior work, we describe the construction of our prototype and propose eight interaction techniques based on three different grips of the FlexStylus. We evaluated the absolute bending of the stylus in a controlled study, and compared it with the most common current stylus augmentation—pressure. Our results show that deformation as a stylus input is promising means for providing parametric input in a drawing application to change stroke width. Finally, we use the results of the study to propose future directions for research incorporating flexible stylus devices.

RELATED WORK

FlexStylus is predominantly inspired by two areas of prior work: augmented styluses and deformable interactive devices.

Augmented Styluses

The stroke qualities of a non-augmented x-y stylus cannot be varied dynamically while the stroke is in progress. This is a considerable disadvantage compared to physical art media, where an artist can manipulate a wide variety of parameters simultaneously to the path of the drawing tool, such as the angle of the pen nib, the tilt of a brush, or the amount of pressure applied. Stylus augmentations such as pressure, tilt, or roll sensing attempt to solve this problem by providing loose physical analogues to the behaviour of traditional media [3,14,15,19,20,28]. These devices tend to use the additional degrees of freedom for parametric control rather than navigation, e.g. pressure for nib size and tilt to represent the tilt of a pastel crayon. This work has graduated from the research stage, and is found in a wide variety of commercial devices, such as Wacom styluses[1], and the Apple Pencil[2].

Researchers proposed numerous techniques for improving menu navigation or scrolling tasks with pressure [14,15,19,20], tilt [28] or roll [3]. Ramos et al. [20] found that users can select up to 6 discrete levels of pressure input. Xiaolei [34] compared tilt and pressure as input methods for manipulating a one-dimensional cursor, finding that tilt was faster, and that pressure movement time and error rate had a strong directional effect, i.e. increasing pressure is more precise than decreasing. Bi et al. [3] determined a threshold of incidental rolling, and the maximum size of a roll-based menu that could be comfortably used with a stylus. Similarly, Xin et al. [35] determined ranges of tilt values that could be comfortably used for target acquisition tasks, followed by similar empirical exploration comparing pressure, tilt, and azimuth.

Other developments focus on making use of hand grips. Studies show there is a close relationship between how users hold a stylus and their intended purpose [14,25], and that users often change grips in relation to the task at hand. Song et al. [25] used capacitive sensing techniques to determine the grip of the user on the stylus. The Conté project [31] took another approach with a similar goal: by designing a rectangular device which resembled a Conté crayon, the researchers enabled users to use different tools depending on which side of the device was touching the screen. Fellion et al. proposed the FlexStylus and discussed how it can be used for continuous parametric input [10]. The current prototype is an extension of their work.

Deformable input devices

Aside from a few exceptions in the domain of musical instruments [23,29], the majority of work concerning deformation as an input technique has focused on devices that take the form of a slate [1,18,22,24,26]. This choice of research direction is owing to recent developments in flexible display technology, and the idea that certain display-related affordances are associated with flexible interactions, such as avoiding occlusion. In addition, currently available flex-detection technologies, such as planar-shaped bend sensors—thin-film resistive sensors [6,9,11,18,26,32], planar strain gauges [1,6], or custom-printed sensors [30] are well suited for planar form-factor devices. These planar sensors can only be flexed along one axis, which makes them ideal for detections with flat surfaces, but difficult to use for detecting multiple axes of bending.

In the domain of flex interactions on a slate device, Burstyn et al. [5] used bend as a continuous input method for navigating stacked data using a flexible prototype. In-depth studies on the specific ergonomics of bending as a continuous parameter control were performed by Ahmaniemi et al. [1], Kildal et al. [16], and Burstyn et al. [6]. These studies were all performed on devices with slate form factors.

Non-Planar Deformation using Fibre-optic Flex Sensing

ShapeTape [2] is a notable example of a sophisticated fibre optic deformation and position sensing system with a non-planar form factor. It is used to model 3D curves using a tool that captures its bending information in 3D space. Herkenrath et al. [13] created Twend, a planar, cellphone-sized, deformable interface device that uses a fibre-optic bend sensing technique similar to the FlexStylus to detect deformation.

FLEXSTYLUS PROTOTYPE

The FlexStylus (Figure 2) device uses a cluster of 4 fibre-optic cables, coupled on one end to a shared 3 mm infrared light-emitting diode (IR LED) (Figure 3, centre). At the base of the stylus, each fibre-optic cable is mounted to a surface mount (SMD) phototransistor, which converts the light level into a measurable current (Figure 3 left). The resulting four signals are sampled by an Arduino Uno[3] microcontroller using four 8-bit ADCs (Analog-Digital Converters). These values can be used to calculate two data points: an absolute value of deformation, which indicates in absolute terms how far the device is flexed, and a value representing the angle of deformation relative to a fixed point on the body of the stylus (Figure 1a).

We selectively abrade each fibre-optic cable to enable it to detect deformation. When assembling the device, we align these abrasions at 90° to one another within the cluster of four cables, so that each abraded side faces directly outwards. If the cable is flexed away from the abraded portion of the fibre-optic cable, a percentage of the light escapes the cable in proportion to the degree of bending

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Figure 2: The FlexStylus Prototype.

Figure 3: Base of Current Prototype (left), tip section (centre), illustration of light behaviour when sensors undergo deformation (right).

(Figure 3, right). Conversely, when the fibre is flexed toward the abraded portion, more light is retained in the fibre.

Prototype Construction
We developed the FlexStylus prototype in an iterative process, beginning with clay mockups for testing interactions, and progressing to a deformation sensing proof-of-concept, a first prototype, and a current prototype. We used fibre optic flex sensing because, due to their flat shape and lack of elasticity, thin film sensors cannot be flexed perpendicularly to their surface normal, which precludes the possibility of using multiple perpendicular thin film sensors.

First Prototype
We designed the first version of the FlexStylus to implement the cluster method of multiple sensors and test preliminary interactions using the flexible stylus device. One of the challenges in building this prototype was that the coupling between cables and phototransistors needed to be very accurate, and due to the overall pen-shape of the device, there was a limited amount of space to work with. To create a physical prototype that complied with the design's constraints of small size and accurate coupling, an iterative process involving the 3D printing of several CAD designs was necessary. We used a Makerbot 2 PLA printer.

Current Prototype
We designed the next prototype to be more modular, allowing the connection of multiple kinds of input processing to the bending sensors, as well as the possibility of reconnecting or changing tips (Figure 3). The main goal of this modularity was to create a prototype system, which could be easily extended and repaired. We preserved the general electronics layout from the initial prototype, however, we redesigned the plastic housing. We made two prominent changes to the prototype design: the removable tip, and the extended rigid plastic section of the body.

The design decision with the largest visible effect on the final stylus revision is the incorporation of a longer rigid section to the body of the. Both iterations of the prototype are approximately 18 cm in length. In the case of the initial prototype, the majority of the device, approximately 14 cm, was composed of a flexible tube. In the new prototype, the flexible portion of the device was 4 cm long, owing to the rigid base, as well as the slightly longer rigid tip. Despite the
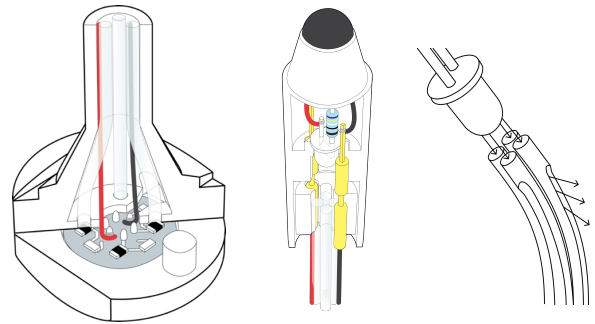
visible difference, this decision had little effect on the performance of the device. On the first prototype, we noted the majority of the deformation took place in the 1/3 (approximately 6 cm) closest to the tip of the device. This is the portion of the device that it is possible to flex while the device is held in a pen grip. The first advantage of the longer base section was to reduce unwanted bending caused by the weight of the phototransistor portion pulling downwards. The second advantage was robustness: a shorter flexible section, while it reduced the active flexible area, also reduced the amount of strain on the components of the device.

The flexible part is slightly elastic—it returns to its initial position when released. This makes the device elastic, with a behaviour close to isotonic devices [7].

INTERACTION TECHNIQUES
According to our observations, the way users grip regular input devices, such as mice, joysticks, or non-augmented styluses, does not have a strong effect on the functional degrees of freedom of the device. However, the input range of the FlexStylus is constrained by grip (Figure 4). With the tool grip, bending requires that some portion of the stylus remain fixed, while the other section moves. In the case of the menu grip, this fixed point is generated by friction between the tip and the surface of the screen, while with the tool grip, the other fingers must provide counterforce to the thumb. For this reason, grip is of considerable importance to the design of interaction techniques. We do not intend to present an exhaustive list of ways to hold a stylus, but more a series of categories connected to different types of interactions on the FlexStylus prototype. Thus far, we have implemented interaction techniques based on three grip types: tool grips, menu grips, and in-air grips.

The tool grip offers the most control over x-y input, but the least control over the angle and magnitude of bend input. The menu grip is associated with a fixed x-y position, but users have a wider amount of control over the angle of bending. The in-air grip allows users to have control over both angle and amount of bending, but does not allow for x-y input. Since our interaction techniques depend on the rotational orientation of the stylus, we placed a black mark on the tip
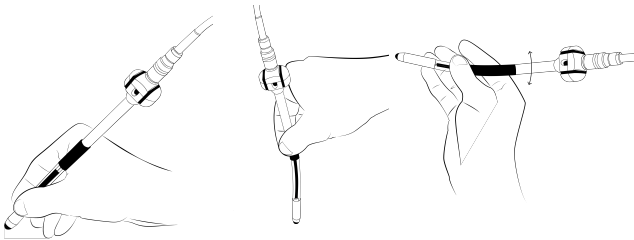
Figure 4: (left to right) Tool Grip, Menu Grip, In-Air Grip.

of the pen to afford the user to align their index finger with it, ensuring they grip the pen with the correct orientation.

The Tool Grip: Drawing and Context Menus

The tool grip is closest to the standard tripod grip, which most people use when gripping a pen [25]. We use the tool grip for drawing related interactions.

Augmented Drawing

Digital drawing uses several continuous parameters, such as brush size, hue, light, saturation and transparency. With a basic stylus, the user cannot control any of these parameters while drawing. Most drawing tablets augment this basic functionality using pressure on the tip of the device to control one parameter. Previous studies showed that users can control both pressure and tilt [12] or grip [27] simultaneously while drawing. We propose that deformation be used to control one or two of these parameters (Figure 1b).

Context Menus While Drawing

In a typical drawing application, the user selects a brush shape and size, as well as a colour. When they want to change one of these parameters, they must select another value in the appropriate toolbar. Alternative toolbars such as Toolglasses [4] avoid round trips between the drawing area and the toolbar. However, these alternate toolbars require either another pointing device or a mode toggle to avoid cursor movements. FlexStylus offers a secondary pointing method using a single one-handed device.

When drawing, the user grips the stylus like a pen to easily control the tip position on the tablet. The range of possible angular bends is restricted when using the tool grip. Rather than being able to rotate the device freely, the user is limited to applying force on the device using one finger at a time, while the device is being supported by the other fingers. While holding the FlexStylus in the tripod grip, users can supply continuous input using either the thumb or the index finger. Context menus for use while holding the device with the tool grip must be designed to accommodate these limitations. For these contexts, we propose a menu consisting of L-shaped gestures [21]. Pressure on the x-axis of the device (i.e., the thumb in the conventional tripod grip) allows the maneuvering of the cursor over various menu items, while pressure on the device in the y-axis (i.e., the index finger), allows for the selection of those menu items. Furthermore, since this y parameter is a continuously variable value, users can use the degree of bending to make parametric selections within the menu item. For example, the user uses thumb pressure to cycle through the context menu, eventually finding the brush size modifier. Then, the brush size can be selected with precision using pressure from the index finger.

The Menu Grip: Menus and Selections

The user can also grip FlexStylus by holding the rigid section closer to the base of the device (Figure 4). This menu grip is useful because it allows users the opportunity to make use of the full range of angular degrees of freedom.

Radial Menus

The menu grip enables interaction with menus, such as radial or marking menus [17] (Figure 1e). The user selects the menu element by angling the FlexStylus in the direction of the element, then bending the device past a bend threshold. An advantage of using the secondary "bend cursor" for interacting with radial menus is that it allows the user to make menu selections without changing the position of the stylus in the x-y axis. This allows the artist to avoid continually switching attention between the drawing canvas and a toolbar, and to maintain stylus position in the event of choosing a new tool while drawing.

Selection Interactions

We added a button to the FlexStylus prototype to enable selection interactions when crossing gestures cannot be used. This is used in menus that do not offer a series of discrete options, but instead a continuum of possible selections. An example of one such menu is a 2-dimensional colour wheel, where the angle of the bend determines colour hue, and the degree of bend determines colour saturation (Figure 1d). Since the precise position of the stylus is important, the button is employed to allow for selection operations without changing the bend state of the stylus. It is worth noting, however, that adding a button is not ideal; the force required to depress the button causes the amount of deformation to change slightly, which is detrimental for precise selection. We propose an alternative in the form of a capacitive touch sensor, which would allow the user to lightly touch the device to make selections without changing the device's bend state. This, however, has not yet been implemented.

Gesture Input

Using the secondary pointer created by the combination of bend angle and amplitude, and the $1 Unistroke Recognizer [33], the system is able to detect a variety of gestures. We propose two uses for gesture detection. One pertains to state changes. We specify a particular shape gesture that, due to the limitations of bending input with other grips, indicates that the user is holding the stylus in the menu grip. The second use of gesture detection for selecting specific commands, similar to gestures with any other pointing device. In the context of drawing, we suggest that primitive shapes be used for drawing those same shapes, i.e., users can select the circle tool by bending the device such that the secondary pointer describes a circle (Figure 1c).

The In-Air Grip: Navigation and Scrubbing

The system enters the state corresponding to an in-air grip when the user removes the stylus from the tablet, yet continues to provide deformation input. Removing the stylus from the tablet limits the kinds of grips possible: for instance, the menu grip cannot be used because the user is not able to use the friction of the surface to provide the counterforce necessary to bend the device precisely. However, it enables the in-air grip; by balancing the bend force between the two fingers, and pressing with the thumb, the user can roll the device between their fingers.

These in-air interactions are ideally suited for navigation operations, as navigation operates using relative motion more than through direct mapping in the way that a pen tool would. This squeeze and roll technique can be used in any situation where there are two linear directions as well as an absolute magnitude. We use the change in bend rotation (the angular motion's direction) to determine the direction of unidirectional scrolling (i.e. to scroll up and down a document), while the size of the bend can be used to control scrolling rate. The scrolling interaction can be extended to include any kind of similar navigation, such as scrubbing. For example, in the context of a drawing program, a user could use this type of operation to cycle through an animation or through different paintbrush tips.

EXPERIMENT

We experiment the precision for absolute mapping of a degree of freedom to a parameter, since it is a widespread interaction technique with graphic tablets. We look at absolute bending in this study (as opposed to angle of deformation), because it is most similar to the most commonly used pre-existing stylus augmentation—pressure. Both absolute bending and pressure are analog input values defined as a distance from a neutral resting state, while there is no analogous input for angular bending input with a typical pressure-augmented stylus. We compared the performance of the FlexStylus against that of a standard commercial pressure-sensitive stylus from a Microsoft Surface Pro 2[4]. While Zhai's work [36] generalizes rate control as being preferable for isotonic and elastic devices, we considered the task appropriate, because the specific interaction in which a user alters the width of a brush is a widely-used implementation of pressure input with a pen.

Task

We performed a 2 x 3 x 3 within-subjects study with 2 INPUT METHODS (BENDING or PRESSURE), 3 TARGET FUNCTIONS (SQUARE, SINE, TRIANGLE), and 3 FUNCTION SIZES (SMALL, MEDIUM, LARGE). Participants repeated each trial 6 times. Our dependent variable was DISTANCE FROM TARGET, measured as the absolute difference between the user's input and the target, in pixels (1 px = 0.12 mm). We removed the first and last repetition from each trial, leaving 4 repetitions. The first repetition was removed so that measurements began when participants were comfortable with the trial. The last
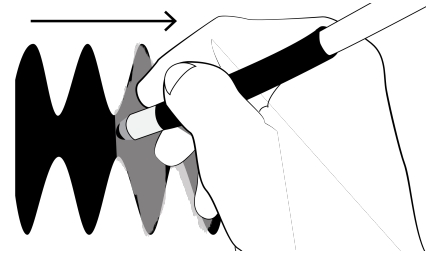

Figure 5: Experimental task. The black area represents the repeating target function, scrolling left to right. The grey area corresponds to participant input.

repetition was removed to reduce any effect that the approaching end of the trial might have on results. The study design resulted in a total of 324 trials (2 x 3 x 3 x 18 participants), of which 2 (0.6%) were missing at random due to recording error.

We asked participants to modulate the stylus input to match a scrolling target function, while holding the input device still in approximately the centre of the screen (though this was not formally constrained) (Figure 5). Visual feedback consisted of a grey function that extended rightward from the stylus as time passed. The resulting feedback was a shape representing the user's input over time, superimposed with transparency over the target function. The upper and lower halves of the screen were mirror images of one another, to resemble a use case where the user varies stroke width. For simplicity, we will describe target and input values as distances from the centre of the screen.

We instructed participants to hold the device in a comfortable way that they could write or draw with. While participants used a variety of grips, they would all be classified as falling under the tool grip category of our grip classification system. To avoid the weight of the FlexStylus cable interfering with observed deformation measurements, it was supported above the stylus with a stand.

Protocol

We asked participants to sit at the experimental system, a Microsoft Surface Pro 2. We explained the task, and performed a brief demonstration. After completing the tasks with one input type, we provided participants with a feedback questionnaire with Likert scale responses. The questionnaire accompanying FlexStylus trials also included feedback questions on the dimensions and physical qualities of the prototype. After having completed both segments of the task (pressure input and deformation input), participants answered a questionnaire containing comparison questions. In total, the experiment took approximately one hour.

We transformed the raw input values from both devices so that the maximum pressure or deformation would provide approximately equal values that were 40% larger than the maximum target value. The Microsoft Surface Pro 2 stylus is capable of discriminating between 10 bits (1024 discrete
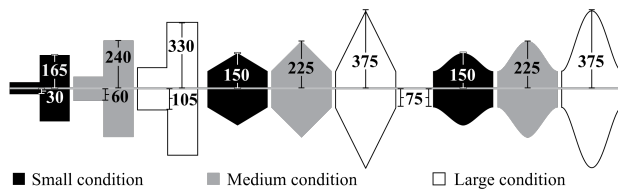
Figure 6: Target functions and sizes (in px). Each function shown was repeated 6 times, with the first and last repetitions discarded.

values) of pressure input. Because of the way that we calculate input from the FlexStylus, input values are not discretized in the way that they are with the pressure stylus. However, both devices were capable of registering input at a fine enough resolution that we did not consider the minimum input threshold to be a determining factor for participant accuracy.

Target Functions
We chose to study 3 functions as targets. Each function was associated with 3 amplitudes. Anticipating that bending and pressure may have different strengths and weaknesses depending on context, we chose the functions to study specific kinds of input variation. Each type of function also had an associated practice function, with a different amplitude and wavelength from the other functions. Users performed the trial once using the practice function before beginning a series of trials.

The **triangle function** consists of a constant positive slope, followed by an inverse, constant negative slope. We chose this function to measure accuracy when the target is changing by a fixed amount over time. We were interested in participants' ability to maintain a continuous rate of change using the device.

The **square function** consists of two amplitudes, a minimum, and a maximum, with the target amplitude alternating between them. The square function serves two purposes: to observe users' ability to maintain a single amplitude of input over a given time period (static accuracy), and to observe users' ability to rapidly and accurately change between two amplitudes of input (dynamic accuracy), as a function of the size of the jump between amplitudes.

In the **sine function** condition, the target amplitude is described by a sine function, adjusted so that the target has the same range of values as the triangle function of the same size. The most common current use for pressure-based stylus augmentation is dynamically varying stroke width. Because varying stroke width generally does not involve the kinds of sudden changes associated with the triangle and square functions, the sine function is closer to everyday use of pressure-based stylus augmentation than the square or triangle functions.

Hypotheses
The distance of travel of a commercial pressure-augmented stylus is very small; the hand moves less than 1 mm between

completely depressing the pressure sensor and releasing pressure. Compared to this distance of travel, the amount of physical movement between a neutral and high-input state with the FlexStylus is higher (> 1 cm). We hypothesize that the increased effort required to move the FlexStylus, rather than making changes more difficult, will make the device more precise, due to the extremely small distance of movement required to make precise pressure selections (**H1**).

Prior research [34] has demonstrated that pressure input is strongly unidirectional—pressure input tends to be more accurate when participants are increasing pressure than when they are reducing pressure. We anticipate that input using the FlexStylus will exhibit a smaller unidirectional tendency than pressure input (**H2**).

We were interested in whether the magnitude of the static input had an effect on input accuracy, and whether the input device used would modulate this effect. With respect to dynamic accuracy, we considered it likely that for both input conditions, the difference between input and target would increase based on the distance travelled (**H3**).

Participants
18 participants took part in the study (18-39 years old, mean=23, sd=5.56). All were right-handed, and physically able to grip a pen. We compensated them $10 for participating in the study. We received ethics clearance from the university research board for this study.

RESULTS
We present overall accuracy results, then we isolate sections of function conditions to examine differences in accuracy between the FlexStylus and the pressure stylus in specific contexts.

Overall Distance from Target Results
We performed a repeated measures factorial ANOVA to determine the effect of the conditions on absolute accuracy, expressed as average absolute DISTANCE FROM TARGET in pixels. We found that INPUT METHOD had a significant effect on DISTANCE FROM TARGET ($F(1,15) = 11.13$, $p = .005$). The INPUT METHOD was also associated with mean large effect size (partial $\eta^2 = .876$). The mean DISTANCE FROM TARGET was 19.81 px with BENDING and 24.79 px with PRESSURE. The analysis does not reveal any interaction between INPUT METHOD and any other factor. The interaction of TARGET FUNCTIONS and FUNCTION SIZES had significant effects on DISTANCE FROM TARGET (respectively $F(2,30) = 10.9$, $p < 0.001$ and $F(2,30) = 86.8$, $p < 0.001$). However, these measures are not particularly useful in themselves for the purpose of comparing input methods given the lack of significance in the interaction of those factors with INPUT METHOD.

Bidirectionality in Sine and Triangle Functions
We wanted to discover if an increasing or decreasing target slope had an effect on accuracy, and if so, if this effect differed depending on the input device used. We converted the data we collected into 2 factors: INPUT METHOD and

DIRECTION (INCREASING or DECREASING), and restricted TARGET functions to TRIANGLE and SINE.

We performed a repeated measures factorial ANOVA and observed that DIRECTION had a significant effect on DISTANCE FROM TARGET ($F(1,17) = 14.050$, $p = .002$), with a large effect size (partial $\eta^2 = 0.454$). INCREASING data points had a mean DISTANCE FROM TARGET of 17.20 px, whereas DECREASING data points had a mean DISTANCE FROM TARGET of 24.57 px. As before, we observed a significant effect of INPUT METHOD on ACCURACY ($F(1,17) = 52.580$, $p < .001$), with a large effect size (partial $\eta^2 = 0.756$). However, we did not observe a statistically significant interaction between INPUT METHOD and DIRECTION.

Static and Dynamic Accuracy in Square Function
We selected the square wave function to test dynamic and static accuracy.

Static Accuracy
We used 6 different target amplitudes with the square wave condition to determine if the amplitude of a static target had any effect on participants' ability to match that target, and if this effect was altered based on input device. We pre-processed the collected square wave trials to remove a buffer area of 20 pixels in each direction around each change in target size, to reduce the effect of correction after rapid changes in input (dynamic segments).

We performed a repeated-measures factorial ANOVA with two factors: INPUT METHOD (2), and STATIC TARGET SIZE (6). We found no significant effect on accuracy for the size of the target.

Dynamic Accuracy
Using the separated out dynamic segments from the square wave function—in which the target rapidly shifts by a specified distance—we ran a repeated-measures factorial ANOVA with two factors: INPUT METHOD (2), and DISTANCE OF TRAVEL (3: 135 px, 180 px, 225 px). We found that DISTANCE OF TRAVEL had a significant, large effect on DISTANCE FROM TARGET ($F(1.62, 34) = 31.17$, $p < 0.001$, partial $\eta^2 = .647$). We also found a statistically significant linear correlation between DISTANCE OF TRAVEL and DISTANCE FROM TARGET ($F(1) = 63.061$, $p < .001$, partial $\eta^2 = .788$), indicating that as distance increases, DISTANCE FROM TARGET decreases, confirming **H3**. However, we did not find a significant interaction between device and distance.

Perceptual Results

User Preference
We asked participants to indicate which device that they preferred in terms of accuracy, comfort, and overall preference, selecting the FlexStylus, the pressure stylus, or no preference (Table 1). Removing the no-preference responses and performing a binomial test of proportions, we found a statistically significant preference for the FlexStylus

Table 1. Input Device Preference Results.

Criteria	FlexStylus	Pressure	No pref.	Binomial sig.
Accuracy	17 (94%)	1 (5%)	-	.000
Comfort	10 (55%)	7 (39%)	1 (5%)	.629
Overall	13 (72%)	3 (17%)	2 (11%)	.021

in the categories of accuracy ($p < .001$) and overall preference ($p < .021$).

Likert-Style Responses
Participants had a general overall preference for the FlexStylus in response to the following prompts: "I found the stroke (grey area) clearly matched the movements of my hand," and "I found the device to be enjoyable to use," (Figure 7). With respect to the FlexStylus, participants also tended to disagree more with the statement that it was difficult to change the magnitude of input.

However, they found the FlexStylus slightly more physically difficult to use, and they also had a larger tendency to disagree with the statement that they would use a similar device if possible.

DISCUSSION
The results of this study, both pertaining to participant accuracy and perceptual responses, strongly suggest that deformation is a promising means for providing parametric input in a drawing application to change stroke width. More generally, absolute deformation appears to be a promising interaction technique for accurate input in a tablet context, which could be exploited for interactions beyond parametric input, such as menu navigation.

Improved Performance with Flexible Stylus
We confirmed our hypothesis (**H1**) stating that participants would exhibit improved performance with the FlexStylus. We offer two explanations for improved participant performance. The first is Control/Display gain (C/D gain) — the fact there is a larger motion in real space associated with the FlexStylus than with the pressure stylus. The second explanation is the continuous haptic feedback that the FlexStylus provides to the user.

The C/D gain of the FlexStylus was set higher than necessary to ensure that participants would not over-bend the device
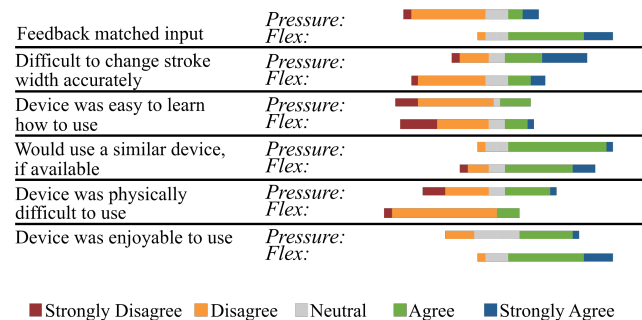

Figure 7. Likert scale feedback, showing proportions of responses for each type of stylus tested.

and damage the sensors. Despite this, the FlexStylus has a much smaller C/D gain than the pressure stylus: while the pressure stylus does translate linear motion into input, the actual distance of this motion is almost imperceptible to participants. While studies on the relationship between C/D gain and input accuracy have had varying results in different contexts [8], the very small movement in space of the pressure stylus represents an extreme case, at the threshold of users' ability for precise differentiation. Since a larger movement in space translated to the same amount of input on the screen, it was easier for participants to distinguish between levels of flex input. We think it is possible that choosing a less conservative C/D gain may result in further improvements to accuracy, but the optimum mapping still must be studied.

Another explanation for the improved performance with the FlexStylus is the inherent haptic feedback of the device. One participant verbally alluded to this haptic feedback during the study, stating that it was easier to remember how much to bend the device as opposed to how much pressure to apply, because they could remember the position of their thumb in space, rather than having to rely on the visual feedback to determine input magnitude. This supports previous research [1], as well as general theory behind the choice of deformation as an interaction method, which states that the inherent (passive) haptic feedback improves users' ability to bend devices to a specific magnitude.

Our second hypothesis (**H2**), that the FlexStylus would exhibit a smaller variation in accuracy than the pressure stylus depending on if the target slope was increasing or decreasing, was not supported by results. We suggest this effect is because while the user is releasing bend input, the fingers and thumb do not experience resistance from the FlexStylus. The resulting lack of feedback is parallel with the pressure stylus. In the case of the pressure stylus, the hand holding the device does not experience the resistance of the tablet screen while releasing pressure. We thought the directional effect would be reduced by the user's ability to feel the stylus's bend configuration in the hand at all times, but our data suggests this is not the case. This result is important for the design of future interactions, as it will be necessary to avoid interactions in which the user is forced to reduce the amplitude of bend input in a precise way. The menu-related interaction techniques described in this paper involve making selections by bending the stylus away from a neutral bend state, so increases in bend are much more likely than decreases. We suggest that future interactions be designed to continue this pattern.

When analyzing the static and dynamic segments, we confirmed the third hypothesis (**H3**) indicating a link between the distance travelled and dynamic accuracy, but found no interactions with the input device in either segment. This indicates that the target size, and the distance to the target had a similar effect on accuracy regardless of which stylus was used.

Limitations

In the interest of isolating deformation as an input method, we did not study movement of the stylus itself in the x-y plane concurrent to input. Until running further studies, we cannot say for certain whether the improvements in accuracy over a pressure-sensing stylus will carry over to tasks in which the user is moving the stylus simultaneously. We also chose not to study the second degree of input freedom, angular input.

CONCLUSION

We created the FlexStylus with the goal of improving the user experience of digital artists by incorporating 2 degrees of deformation sensing. Adding deformation as an input method is intended to allow users to make more precise parametric input during drawing, as well as to enable precise pointing interactions (such as radial menus or colour pickers) without moving the stylus in the x-y axis. We were interested in how the unique properties of deformation input, such as continuous built-in haptic feedback, might improve user accuracy in a task involving matching a target stroke width. We found that deformation offered significant improvements in accuracy over a conventional pressure-detecting stylus device.

With respect to interaction techniques, future work involves implementing multi-level marking menus, allowing for flex-gesture-based input without visible menus for expert users. We are interested in determining if the benefits of these menus for mouse devices apply equally to interactions with the flex cursor. Future studies will examine parametric input occurring simultaneously to changes in the x-y position of the device, to more closely match situations where a user is modifying brush parameters while drawing. We will also evaluate users' accuracy using the angular deformation degree of freedom. To perform a study comparing the FlexStylus to previously studied styluses, we will compare angular deformation input against a suitable pre-existing augmented stylus input type. For this purpose, we propose a tilt detecting stylus, since tilt-detection is another type of stylus augmentation that offers directional control. We believe that the angular bend detection is a promising and relatively-unexplored research domain for a variety of contexts, and invite other members of the HCI community to consider this input modality for systems requiring fine-grained directional and amplitude control with inherent haptic feedback.

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