Glissade: Generating Balance Shifting Feedback to Facilitate Auxiliary Digital Pen Input

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ABSTRACT

This paper introduces Glissade, a digital pen that generates *balance shifting feedback* by changing the weight distribution of the pen. A pulley system shifts a brass mass inside the pen to change the pen's center of mass and moment of inertia. When the mass is stationary, the pen delivers a constant yet natural sensation of weight, which can be used to convey a status. The pen can also generate a variety of haptic clues by actuating the mass according to the tilt or rotation of the pen, two commonly-used auxiliary pen input channels. Glissade demonstrates new possibilities that balance shifting feedback can bring to digital pen interactions. We validated the usability of this feedback by determining the recognizability of six balance patterns – a mix of static and dynamic patterns chosen based on our design considerations – in two controlled experiments. The results show that, on average, the participants could distinguish between the patterns with a 94.25% accuracy. At the end, we demonstrate a set of novel interactions enabled by Glissade and discuss the directions for future research.

Author Keywords

Haptics; Digital Pen; Balance Shifting Feedback; Sensation of Weight.

CCS Concepts

•**Human-centered computing** → **Haptic devices;**

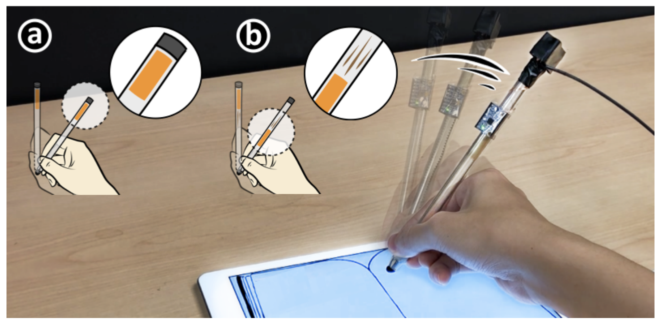

Figure 1. The ungrounded pulley system of Glissade translates a brass cylinder along the barrel of the pen, enabling the pen to create both (a) static and (b) dynamic balance patterns.

INTRODUCTION

Digital pens have become important input devices for surface computing. In addition to sketching and writing, a digital pen can be used for interacting with graphical user interfaces with precision, an alternative for a computer mouse. The pen can also be used as a probe for interacting with on-screen virtual objects. Furthermore, researchers have investigated haptic outputs for digital pens to promote realism in handwriting tasks [4] or enhance interactions with GUIs [19, 20]. User evaluations from these studies indicate that haptic feedback enhances the usage experience and usability of digital pens.

In this paper we aim to enhance auxiliary pen input through the application of haptic feedback. Such input methods allow users to switch between different modes or adjust parameters efficiently by tilting and rotating [39, 40, 45], rolling [2, 23, 37], or pressing the pen [21, 27, 29, 33]. Facilitating auxiliary pen input also saves screen space by reducing the usage of GUI widgets. However, a haptic output that directly corresponds to auxiliary pen input, remains to be explored.

We introduce Glissade, a pen that can linearly translate a mass inside its barrel by means of a pulley system, a mechanical design that has been proven effective in providing ungrounded kinesthetic feedback (*e.g.*, [34, 46]). As illustrated in Figure 1, the user would either feel a certain static balance pattern, when the pen's balance is stationary, or a dynamic balance pattern, as the pen's balance shifts. The weight sensation stimulates the slow-adapting skin receptors, making it less annoying than conventional vibrotactile feedback. As for the dynamic pattern, the user feels varying weight shifting forces when tilting or rotating the pen, as if the digital information follows the pen's orientation haptically. The aim of this paper is to extend the aforementioned benefits to auxiliary pen input.

We created six balance patterns – a mix of static and dynamic balance patterns, for auxiliary pen input. Two controlled ex-

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periments were conducted to verify the utility of providing balance shifting feedback when engaging different auxiliary pen input channels. Among many of the channels, we initiated an exploration of a haptic output that closely corresponds to the user's manipulation of digital pen orientation, *i.e.*, *pen tilting* and *pen rotating*. Results show that the average recognition rate for tilting and rotating the pen on a surface are 94.4% and 94.7% respectively. This suggests that the balance patterns are perceivable and recognizable during pen orientation manipulation, which opens a wide range of new interactions. Finally, we demonstrate the usability of Glissade in auxiliary pen input and other potential applications, such as gaming and notification.

In summary, the main contributions of our work are: (a) an investigation of the unexplored area of haptic feedback for digital pen orientation manipulation, (b) the design considerations and technical design for making a digital pen capable of shifting its own balance according to the pen's orientation, (c) a verification of the usability of balance shifting feedback by means of examining users' ability to recognize different balance patterns as they tilt or rotate the pen, and (d) the demonstration of several novel interactions enabled by applying *balance shifting feedback* to digital pens.

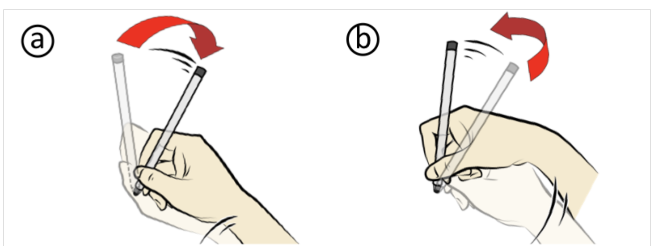

Figure 2. Two auxiliary pen input methods are examined: the actions of (a) pen tilting (altitude) and (b) pen rotating (azimuth).

RELATED WORK

Input with Digital Pens

Researchers have explored the use of pen-tip pressure for mode switching [21, 27], menu selection [29], and adjusting parameters [33].

The orientation of the pen can function as channels for auxiliary input as well. Prior research suggests intentional pen rolling [2, 37] augments menu item selection. As for tilt, researchers have utilized the altitude and azimuth of the pen's orientation for a variety of interactions. Tilt Cursor [39] and Tilt Menu [40] allow users to manipulate graphical widgets and to control a cursor to select menu items. Furthermore, Xin *et al.* conducted an empirical study to evaluate users' ability to control pen tilting in pen-pointing tasks [45]. Their result suggests that pen tilting can enable a plethora of pen interactions. On top of research on individual input channels, Hasan *et al.* explored the combination of pressure, rolling, and tilting [9] and found that users could utilize pressure and tilting conjunctively for efficient menu selection tasks.

Although, the azimuth orientation can also be regarded as a sub-dimension of tilt, this paper regard the altitude orientation as a pen tilting channel and the azimuth orientation as a pen rotating channel and investigate both of them (Figure 2).

In addition to the diversity of digital pen input channels, the workspace in which input can be made extends from the surface to the air, owing to technological advancements and much research effort. With the emergence of 3D tracking technology, researchers have developed digital pen interactions in which users could manipulate widgets [7] or interactive layers [36] in midair. Later researchers have further proposed other 3D tracking mechanisms, such as infrared [8] and magnetic tracking [3], to enable more fine-grained 3D interactions.

Fusing the study of various input modalities and workspaces together, Hinkely *et al.* explored the design space of motion-based pen input and proposed combinations of different pen gestures in various workspaces, yielding a variety of applications [12].

Haptic Feedback on Digital Pens

Previous works have explored the application of tactile and kinesthetic force feedbacks on digital pens. These feedbacks enable a variety of interactions.

Tactile feedback on digital pens enriches human-computer interactions. Prior research has shown that generating vibrotactile feedback on digital pens provides better interaction experiences with GUI [1, 16, 19, 20]. Furthermore, much study has been performed on the generation of the perception of on-screen textures with digital pens. Kyung *et al.* proposed integrating a miniature pin array into a digital pen [16, 17, 18], enabling users to feel virtual textures through the 2.5D shape rendered by the pin array. Other researchers proposed generating vibrotactile or audio-vibrotactile patterns to simulate virtual textures [5, 31] or natural writing experience [4]. Still other researchers utilized electrovibration technology to simulate pen-on-paper experiences[41, 42]. This technology generates varying frictional force to the pen as it slides on the display by modifying, through electrical attraction, the normal force between the pen and the display.

Adding kinesthetic force feedback on digital pens also enables numerous applications. Digital pens that generate kinesthetic feedback often serve as probes for interacting with 3D virtual objects. PHANToM, a grounded digital pen, can generate a diversity of force feedback [15, 25, 26] to inform the user of the shape or stiffness of a virtual surface. ImpAct [43] and Pen De Touch [14] are two ungrounded digital pens that also provide kinesthetic force feedback. The former is a standalone, pen-shaped device that linearly actuates a rod against the display to produce normal forces. The latter is a pen-shaped device that bends itself to exert forces on the user's fingers [14], providing ungrounded (or body-grounded) kinesthetic force feedback for probing virtual objects in midair. In addition, Airwand [30], a pen-like device, also generates ungrounded kinesthetic force feedback to enrich interaction with virtual environments, but it requires additional pneumatic systems, which reduces mobility. Aside from providing feedback during interactions with virtual objects, kinesthetic force feedback can also serve as guidance in interactions with GUI, such as the case in the study of Park *et al.* in which they use an electromagnetic apparatus to provide the user with kinesthetic force feedback when the pen is hovering above the surface [24].

Balance Shifting Feedback

In this paper, we investigate the application of a novel haptic feedback on digital pens, balance shifting feedback, to enrich interactions. The balance shifting feedback can be achieved through modifying the weight distribution of the feedback-providing device. This type of feedback has been used in different contexts. Hemmert *et al.* presented a haptic display by changing the gravitational properties of a device on a mobile phone [11] for GUI augmentation, ambient display, and haptic pointing. Furthermore, changing the perception of the device's weight [32, 34, 46] makes balance shifting feedback especially useful in virtual reality or augmented reality applications. Also, TorqueBAR [38], an ungrounded device with a computer controlled center-of-mass, enhanced computer system interaction. For everyday-life interaction, Hirose *et al.* proposed a system to augment taste sensation through alluding to the weight of food by changing the weight distribution of the fork [13].

GLISSADE DESIGN AND IMPLEMENTATION

We created a fully functional prototype, Glissade, as a probe to investigate how to apply static and dynamic balance patterns on digital pens. In this section, we discuss the design details we considered and present the process we went through to create the prototype.

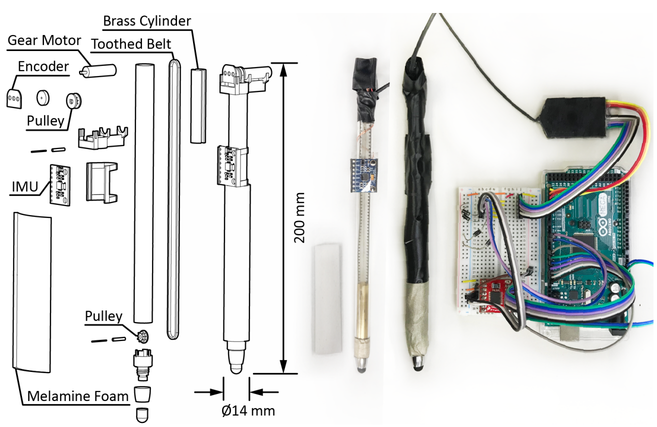

Figure 3. The Glissade prototype: The entirety of the prototype is made opaque by wrapping black tape around it.

Design Considerations

Vibrotactile vs Balance Haptic Feedback. Balance haptic feedback has several unique advantages over other haptic feedback such as vibrotactile feedback. It can represent weight or be used for expressing a state or information that will persist for some time. When applied to simulate objects with different inertia, users would feel the difference in inertia as they would in real life, which cannot be achieved by most haptic feedback. When used to express a persisting state or information (*e.g.*, how much time is left), balance haptic feedback creates little disturbance to the user because balance is a natural property of pens. The ability to provide unobtrusive haptic feedback makes it a better choice than vibrotactile feedback, which may annoy or disturb the user if persistent [10, 22].

Shape and Size of Glissade. We designed the shape and size of our prototype according to prior ergonomic studies. First, Glissade adopts a circular cross section because it is more preferable [6] than other shapes. Moreover, in accordance with researchers' suggestions on pen length and diameter [6, 44], we designed the pen to be of a length close to that of the length of popular digital pens (e.g. Apple pencil: 176mm) and a diameter close to 8mm.

Weight of Mass. Considering the aforementioned shape and size, we created several lo-fi styli (circuilar shape, diameter: 10mm, length: 200mm) each with a different adjustable brass mass inside. In a pilot study, we iteratively adjusted the mass position and asked three participants (1 female) to write and draw with each stylus. The participants were asked to report if they agree that the stylus is acceptable for daily use. Their feedback approximately suggests that when the mass is below 15g, the brass mass is acceptable in any position. Thus, we used a brass mass close to 15g for the Glissade prototype.

Maximizing Weight Shift. We took several measures to maximize the range of balance without making the pen excessively heavy. For parts that do not contribute to balance shifting, we used thin, small, and lightweight materials. We also chose to change balance by actuating a dense metal cylinder that tightly fits the pen barrel. Because cylinders occupy the least longitudinal space in a round barrel, there is more room for weight shifting. Moreover, we further reduced pen weight by supplying power via a lightweight wire bundle instead of installing batteries.

Distribution of Components. Although placing components, such as the motor, near the tip of the pen would allow a greater range of balance, this would vastly enlarge pen size and thus make it hard to grip. Therefore, we have chosen to position the motor at the back of the pen and the IMU as close to the tip as possible without interfering with the grip.

Prototype Implementation

As illustrated in Figure 3, Glissade comprises a conductive pen tip, a cylindrical pen body, a belt and pulley system, a rotary encoder, an inertial measurement unit (IMU), and a controller that is connected to the pen via wires. The motor on Glissade drives the belt and pulley system to actuate the balance-shifting mechanism, and the controller processes measurements from the rotary encoder and IMU, communicates with a computer, and regulates the rotation of the motor.

The net weight of the pen, including the wires, is 29.6g. All components at the end of the barrel (including the wires) were carefully chosen and designed to be light-weight (3.9g in total). The brass cylinder (14.4g) can be adjusted to any part of the barrel. This gives the entire pen's center of mass the range of 83–142 mm away from its tip, with the 83 mm being comparable to that of common posted pens and markers. The corresponding range of moment of inertia (with respect to an axis perpendicularly passing through the pen tip) is 3.15×10^5–6.41×10^5 g mm^2.

The barrel of the pen is a 170mm long, 1mm thick acrylic tube with a 10mm outer diameter. The entirety of the tube is made opaque by wrapping black tape around it. The frontal part of the barrel is padded with a 2mm-thick melamine foam (wrapped with black tape) to minimize vibration concomitant with motor activity. Although this design gives Glissade a diameter slightly larger than suggested by prior studies [6, 44], participants of our study did not report any discomfort when using our device.

The conductive pen tip is made up of a conductive rubber nib (5.5mm in diameter) fixed on a 3D printed structure with a piece of conductive plastic. This pen tip structure is attached to the front end of the barrel. A piece of conductive cloth, in contact with the conductive plastic, covers the frontal part of the pen. This design enables users to use this stylus on a touch screen whenever the fingers are in contact with the conductive tape.

The belt and pulley system consists of a 1.5mm-wide rubber toothed belt, two 3D printed stationary PLA toothed pulleys, a micro planetary gear motor (ZWPD006006-136), and a cylindrical brass mass with two trenches on its sides. The motor is fixed at the back of the pen barrel and drives one of the pulleys. The toothed belt, looped over the motor-driven pulley and another stationary pulley at the front of the pen, circulates according to the motor's rotation. The belt is fused with the brass mass with glue in one of its trenches while it moves freely in the other trench. The mass (40.0mm long; 8.0mm in diameter; 14.40g) was chosen so that Glissade's range of moment of inertia mostly falls under the maximum acceptable moment of inertia obtained in our pilot study.

With the aforementioned mechanical design supplying 5.0V to the motor, the maximum speeds that the mass can be translated under two extreme conditions are $75.4\,\mathrm{mm\,s^{-1}}$ (vertically upward) and $87.0\,\mathrm{mm\,s^{-1}}$ (vertically downward). The electric currents supplied when moving the mass vertically upward and downward at maximum speeds are 0.084A and 0.065A respectively.

Finally, a controller implemented on an Arduino Mega2050 board regulates all electronic and mechanical parts of Glissade. It acquires pen orientation information from the 6-DoF IMU (MPU6050) installed on the body of the pen for motion-based pen input detection. It also keeps track of the motor-driven pulley's rotation through a Pololu's rotary encoder set. Using such information, commands are issued from a computer via the serial port, while the controller accurately controls the motor with a PID controller.

The computer can also acquire Glissade's orientation and dictate the mode and related parameters on the controller by sending simple commands through the serial port. This interface enables designers to easily design interactions with Glissade without having to modify the firmware on the controller. The example interactions and demo applications presented near the end of this paper are created using this interface.

DESIGNING HAPTIC PATTERNS WITH GLISSADE

To demonstrate the capabilities of Glissade, we designed various balance patterns that can be used in applications. Six patterns were implemented, including three static patterns: *Front Heavy (FH)*, *Balanced (B)*, *Back Heavy (BH)*, and three dynamic patterns: *Shift Towards the Back (STB)*, *Shift Towards the Front (STF)*, and *Balance Oscillation (BO)*. We explain the considerations as follows.

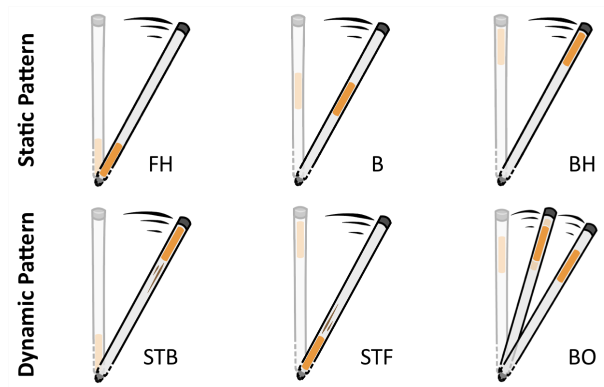

Figure 4. The image illustrates how the six balance patterns function according to the pen tilting input.

Static Balance Patterns

When the pen's balance is static, it behaves like a normal pen. The user can constantly receive the weight perception from Glissade. When using an auxiliary pen input channel, the static pattern can be used to inform the user about a status of the system. For example, when the user rotates the pen for menu selection, she feels the pen is heavy and realizes that she is selecting a level 2 menu item (the pen is lightweight in level 1). Furthermore, static balances are well suited for representing information that needs to be displayed over long periods of time because their passive nature causes less disruption.

The static patterns are as follows:

Front Heavy (FH). This balance is achieved by positioning the mass inside Glissade at the foremost position of the barrel.

Balanced (B). This balance is achieved by positioning the mass inside Glissade at the center of its shifting range.

Back Heavy (BH). This balance is achieved by positioning the mass inside Glissade at the rearmost position of its shifting range.

According to prior research [46], the patterns can induce different levels of weight perceptions, where the user may feel the pen is lightweight with the *FH* pattern. The user will feel that the pen becomes more and more heavy as the mass is positioned further to the back (*B* and *BH* patterns).

Although it is possible to increase the number of static patterns, increasing this number decreases the haptic difference between patterns. Our lab study suggests that participants have trouble identifying the patterns when the number of patterns exceeds 3. In comparison, all of them could learn the aforementioned three patterns in a short time.

Dynamic Balance Patterns

Balance is dynamic when the mass inside the pen is moving. Different balance patterns can be used to convey various information to the user. They are especially suitable for use in conjunction with auxiliary pen input, for example, when the user tilts the pen to increase the saturation of a pen stroke, the mass shifts upwards with the tilt angle correspondingly. This gives the user an increasing kinesthetic feedback correlated with the tilting action.

As an 1D output, the possible moving trajectories of the mass include the upward direction (toward the pen's top), the downward direction (toward the pen's tip), and the combination of both. We decided to implement one of each of the possible trajectories.

Shift Towards the Back (STB). To maximize the kinesthetic feedback from Glissade, we decided to maximize the range of balance shifting and linearly mapped the entire range of positions of the brass mass to a range of 45 degrees in altitude or azimuth. The range of 45 degrees is chosen because we observed in an informal study that tilting a pen on a surface from an upright position towards the pen-holding hand more than approximately 45 degrees is difficult for many users. The bottom of the hand naturally restricts the range of altitude modulation when tilting a pen in that direction.

The relationship between the entire pen's center of mass and the angle change in altitude or azimuth can be described by the equation:

$$D_{CM} = 1.3\theta + 82.7[mm], 0 \leq \theta \leq 45 \qquad (1)$$

where D_{CM} denotes the distance between the center of mass of Glissade and its tip, and θ denotes the angle difference in altitude compared to an upright pen orientation or the amount in degrees the pen has rotated counter-clockwise from its initial orientation.

Similarly, the relationship between the moment of inertia and the angle change in altitude or azimuth can be described by the equation:

$$I = 93.23\theta^2 + 3041.12\theta + 315053.5[\mathrm{g\,mm}^2], 0 \leq \theta \leq 45 \qquad (2)$$

where I denotes Glissade's moment of inertia with respect to an axis perpendicularly passing through its tip.

Shift Towards the Front (STF). Similarly, the relationship between the pen's center of mass and the angle change in altitude or azimuth can be described by the equation:

$$D_{CM} = -1.3\theta + 142.2[mm], 0 \leq \theta \leq 45 \qquad (3)$$

The relationship between the moment of inertia and the angle change in altitude or azimuth can be described by the equation:

$$I = 93.23\theta^2 - 11431.68\theta + 640691.5[\mathrm{g\,mm}^2], 0 \leq \theta \leq 45 \qquad (4)$$

Balance Oscillation (BO)

This pattern is a simple combination of one short backward balance shift immediately followed by a forward balance shift back to the starting balance. This pattern was inspired by our desire to find a suitable feedback for the occurrences of certain short events. It has the advantage of being able to be repeated as many times as required because the brass mass always returns to its original position. Furthermore, because the movement of the mass in the *BO* pattern is smaller than required for most users to perceive the direction of movement (tested in a pilot study), this pattern is also selected for the purpose of exploring how well users would be able to identify, from a pool of other patterns, dynamic patterns involving mass movements smaller than their ability to perceive the movement direction.

The short balance oscillation pattern used in our user study corresponds to a change in the pen's center of mass from 136mm to 142mm (from the pen tip) then back to 136mm (the moment of inertia changes from $5.91 \times 10^5\ \mathrm{g\,mm}^2$ to $6.41 \times 10^5\ \mathrm{g\,mm}^2$ then back to $5.91 \times 10^5\ \mathrm{g\,mm}^2$) whenever the angle change in altitude or azimuth crosses over 22.5 degrees. The oscillation is performed at the highest speed possible and takes approximately 0.46 s to complete. We have chosen for the oscillation to occur under a back heavy condition because we discovered that users tend to distinguish shift in balance better under back heavy conditions.

BALANCE PATTERN DISCRIMINATION TESTS

As the balance shifting feedback is a new type of haptic output on digital pens, we consider it important to investigate how well users can perceive it when using auxiliary pen input. We tested the balance patterns we designed, with an aim to answer the following questions: (a) How well can they distinguish different static and dynamic balance patterns? (b) Would the recognition rates be affected by the way the pen was used, the pen tip's contact with a surface, or extra cognitive load? To gain an initial insight into the answers to these questions, we conducted two independent experiments for two types of pen input: *pen tilting* (Figure 2a) and *pen rotating* (Figure 2b). The study design, procedure, and participants are identical in both of the experiments.

The Considerations of Testing Tilt and Rotation Actions

Compared to other auxiliary input channels, such as pressure or rolling, tilt and rotation involve more pen motion, which induces more perceivable inertial force from the mass inside Glissade. In addition, prior works have shown that these actions enable versatile, efficient pen-based interactions. Therefore, we first focus on these two actions and leave the other input modalities for future work.

The tilt and rotation actions are related to the altitude and azimuth of the pen, respectively. As shown in Figure 4, the user could dictate the altitude of the pen's orientation by changing the angle between the pen and the horizon and control the azimuth of the pen's orientation by rotating the pen about its tip when tilted. The two parameters, although often used in conjunction, are associated with different uses of degrees-of-freedom of the hand and the wrist. Thus, we examine these two parameters in two identical experiments. In the pen tilting experiment, the user would tilt the pen to change its altitude, and the dynamic patterns would be generated according to the altitude of the pen's orientation. In the pen rotating experiment, the user would rotate the pen to change its azimuth, and the dynamic patterns would be generated according to the azimuth.

Experimental Design and Procedure

Each experiment employed a 2×2×6 within-subject factorial design. The three independent variables are Workspace (*On-surface* or *Off-surface*), Secondary Task (*With Cognitive Load* or *Without Cognitive Load*), and Pattern (*FH, B, BH, STB, STF, or BO*). During each trial, participants performed tasks under one of the Workspace × Secondary Task × Pattern combinations.

The Workspace parameter examines whether or not the normal force from a surface in contact with the pen affects balance pattern recognition rates. Participants were asked to modify the pen's orientation either on the desk surface (with the pen tip lightly resting on the surface) or in midair.

In *With Cognitive Load* condition under Secondary Task, participants were asked to divert some of their attention to a secondary task, simulating scenarios in which some attention is diverted to other visual contents.

We used a modified Stroop test [35] as the secondary task. In this test, the name of a color is displayed using a random font color (*e.g.*, the word "blue" displayed in the color red). The text and the color were randomly generated from a pool of five candidates (*i.e.*, yellow, green, blue, black, and red) with a 2 second interval. During the task, participants were asked to count how many times a match occurred between the text and the font color. To ensure that the participants were sufficiently focused on this secondary task, participants were asked to maintain an accuracy of 90% or above on this task. On the other hand, no secondary task was given under the *Without Cognitive Load* condition.

The tests were done in blocks. In each block, a Workspace × Secondary Task combination is chosen, and each block consists of 48 trials as a result of the six balance patterns being presented in random order eight times. The test order of various Workspace × Secondary Task combinations was counter-balanced.

The experimental design results in 2 Workspaces × 2 Secondary Tasks × 6 Patterns × 8 repetitions × 12 participants = 2304 trials (*i.e.*, 4608 trials for the two experiments).

Note that the participants completed one experiment before moving on to the other. The order of the pen tilting and pen rotating experiments was randomly assigned. In general, the participants finished one experiment per day.

Dependent variables for the experiments include the pattern recognition rate and the number of attempts required to identify each pattern.

Apparatus and Procedure

In each experiment, participants were asked to sit in front of a desk, where a 27-inch computer monitor was used to display the experimental user interface (Figure 5). During the entire experiment, the seated participant wore headphones playing white noise so that they could not hear the noise from Glissade's motor.

Participants were briefed about how Glissade operates and were asked to hold the pen at approximately the same place with their dominant hand. The participants were allowed to familiarize themselves with the patterns before commencing the experiments.

Figure 5. The experimental setup.

Participants were asked to tilt or rotate the pen to 45 degrees. Both pen motions were completed in a single stoke. After a participant had completed a stroke, the experimenter would take Glissade out of the participant's hand, and the participant would either request a retry or call out the name of the pattern (note that only the answer of the last retry was recorded). Accordingly, the experimenter would configure Glissade to regenerate the same pattern or generate the next pattern and then set the pen back at its initial position and orientation in the participant's hand. This ensures that the participants' answers were based on what they felt during each stroke and not what was felt between strokes.

By allowing retries, we acquire the absolute ability for users to distinguish patterns (represented by recognition rate) and their confidence in their response (represented by the number of repetitions). As answers are not disclosed when subjects respond, more repetitions does not increase the chance of a correct response if they could not distinguish the pattern. Participants reported that they repeated if a pattern was not felt properly or they wished to confirm the feeling.

Upon completion of the study, participants filled out a post-experiment questionnaire where they indicated subjective ratings for the recognizability of the balance patterns (1: very difficult to recognize, 7: very easy to recognize). Finally, each of them received a semi-structured interview.

Participants

Twelve paid participants (four female), between the ages of 20 and 28, participated in the experiments. Ten of the participants are right-handed. None of them had the experience of tilting or rotating the pen as an auxiliary input.

Results

The resulting data from each experiment were analyzed using repeated-measure ANOVA and Bonferroni corrected paired t-tests for pairwise comparisons.

Pattern Recognition Rate

Pen Tilting Experiment. The average recognition rate across all conditions in which users tilted the pen (pattern generated according to altitude) is 94.27%, suggesting that the balance patterns are distinguishable to the participants (Figure 6). There is no significant three-way interaction between Workspace,

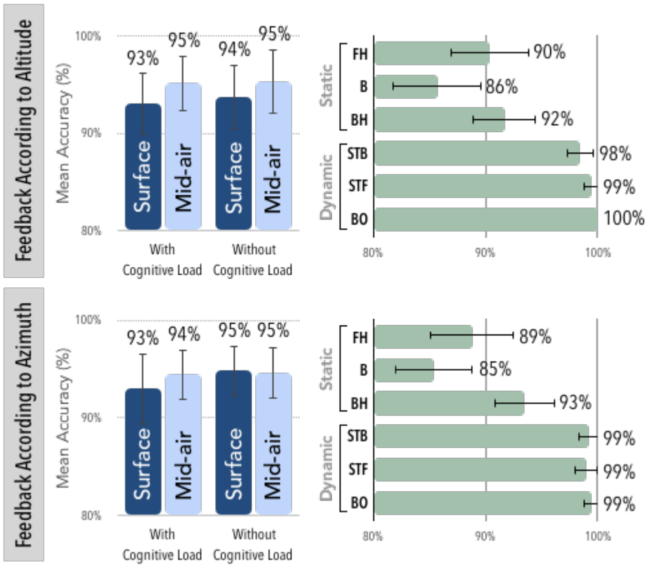

Figure 6. The relationship between recognition rates and various variables of the two experiments: Left: Workspace and Secondary Task; Right: Balance Patterns (The error bars represent standard error in all figures).

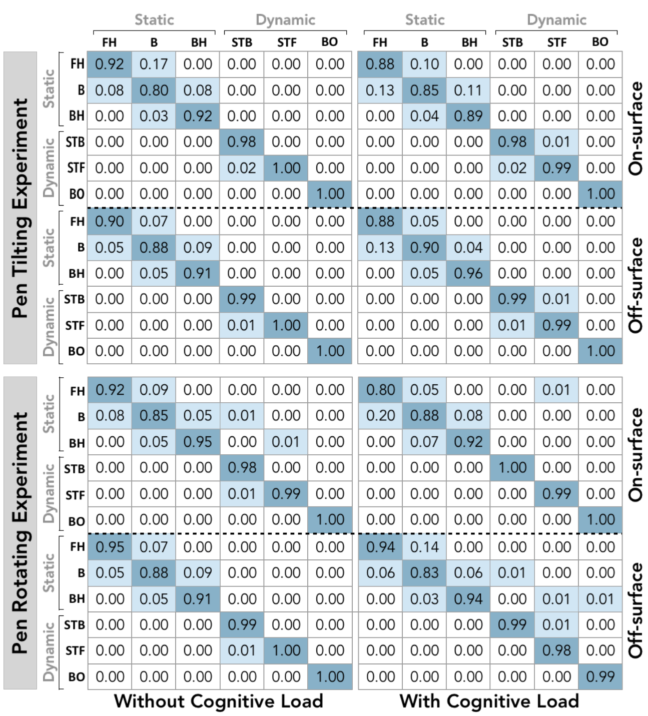

Figure 7. The confusion matrices of the two pattern recognition experiments.

Secondary Task, and Pattern ($F_{2.395,26.344} = 0.69$, $p = 0.536$), neither is there any significant two-way interaction between the three independent variables (all $p > .1$).

Workspace has no significant effect on recognition rates (both $p > .1$), suggesting that participants are able to recognize balance patterns equally well in both on- and off-surface interactions.

Secondary Task also has no significant effect on recognition rates ($p > .1$). We observed that some participants reported difficulties double-tasking while their recognition rates remained unaffected. This may be a result of some users' tendency to "overthink" and second guess when only concentrating on the recognition task, a behavior reported by some participants.

Under our experimental conditions, only Pattern has a significant effect on the recognition rates ($F_{2.176,23.941} = 23.69$, $p < .001$). Performing pairwise comparisons between individual patterns (*e.g.*, *STB* vs *FH*, *STB* vs *B*, etc.) for this experiment, we discovered that the recognition rates of the dynamic balance patterns (*STB, STF, BO*) are significantly higher than those of the static balance patterns (*FH, B, BH*, all $p < .05$). The subjective feedback from the participants and the confusion matrices (Figure 7) indicate that this resulted from the difficulty participants experience when differentiating *Front Heavy* from *Balanced*. No significant differences in recognition rates are found between the dynamic balance patterns we selected, and the confusion matrices further indicate that participants could accurately perceive the differences between these patterns.

In the semi-structured interview, the participants reported that, when performing the input action at a fast speed, *Front Heavy* and *Balanced* sometimes create similar sensations of weight. However, they agreed that if they manipulate the pen at a normal speed, the difference between the two patterns can still be recognized. Also, there were three participants who reported that their performance on *FH* and *B* patterns could be increased if they could "*use the pen daily to get more familiar with the balance perceptions (P1, P5, P7).*"

Pen Rotating Experiment. Similar to the experiment aforementioned, the average recognition rate across all conditions in which participants rotated the pen (patterns generated according azimuth) is 94.23%, and there is no significant three-way or two-way interaction between the independent variables.

Pattern has a considerable impact on recognition rates ($F_{2.414,26.550} = 13.27$, $p < .001$). Pairwise comparisons show that the recognition rates of the *STB*, *BO*, and *STF* are all significantly higher than *FH*, *B*, and *BH* (all $p < .05$). The results concerning the static balance patterns in this experiment and the reasons behind those results are analogous to those mentioned prior regarding the previous experiment. No significant differences are found between the recognition rates of the dynamic balance patterns (all $p > .05$). Likewise, according to the pairwise comparisons and the confusion matrices (Figure 7), the participants could distinguish between the dynamic balance patterns well.

Number of Attempts

On average, participants performed the pen stokes 1.14 and 1.11 times in each trial before confirming their answer in the altitude modifying and the azimuth manipulating experiments respectively. *Pen Tilting Experiment.* There was no three-way or two-way significant interactions between the independent variables (all $p > .05$).

Each independent variable significantly affects the number of attempts (all $p < .05$). Participants spent more attempts in on-surface conditions (M = 1.19, SD = .26) than the off-surface conditions (M = 1.09, SD = .17), suggesting that the normal force from the surface slightly interferes with the participants' perception of balance shifting feedback. Concerning the addition of the secondary task, surprisingly, participants repeated the pen strokes to feel the balance pattern more times under the condition Without Cognitive Load (M = 1.17, SD = .26) than under With Cognitive Load (M = 1.11, SD = .18). This again shows that some participants tend to "overthink" when there is no extra cognitive load. Complete focus on determining which balance shifting feedback was given to them might have increased their tendency to retry feeling the balance patterns they were unsure of. However, note that the assumption of the overthinking problem should be verified with another study. We regard this investigation as a future work.

According to pairwise comparisons between Patterns, the participants tends to be less confident with static balance patterns. The average number of attempts for *FH* and *B* are significantly higher than all of the dynamic balance patterns (all $p < .05$), and the average number of attempts of *BH* is significantly higher than *STB* and *BO*. These results are consistent with the recognition tests, in which participants tended to be confused by *FH* and *B* if they performed the pen action too quickly.

Pen Rotating Experiment. There was no three-way or two-way significant interactions between the independent variables (all $p > .05$).

Workspace and Secondary Task seem to have no effect on the average number of attempts (all $p > .05$). Concerning Workspace, the reason why the surface affects the average number of attempts less in the pen rotating experiment compared to that in the pen tilting experiment could be that the pen motion involved in modifying the azimuth of the pen's orientation is more parallel to the surface. Parallel motion generates less normal force between the pen and the surface, thus generating less interference. As for Secondary Task, the results suggest that participants did not "overthink" as much in the Without Cognitive Load conditions in this experiment.

Only Pattern significantly affects the average number of attempts ($p < .001$). Although not all statistically significant, pairwise comparisons show that the average number of attempts for *FH*, *B*, and *BH* are higher than that of the *STB*, *STF*, and *BO*. The results reinforce the need for more time to get familiarized with the static balance patterns discovered in the pen tilting experiment.

Subjective Ratings

We performed a Friedman signed-rank test with Wilcoxon tests for pairwise comparisons. The Friedman test indicates significant differences in ratings between different balance patterns ($\chi^2(5) = 91.5$, $p < .001$). All of the dynamic balance patterns received significantly higher scores than *Front Heavy* and *Balanced* (all $p < .005$), and there were no significant differences among the dynamic balance patterns.

The median rating for each pattern was no less than 4. This suggests that most of the participants think that the patterns were not too difficult to perceive. Among the patterns, *Balanced* has the lowest average rating (M = 3.98, SD = 1.67), the reasons being the same as those mentioned prior.

Discussion

The results of the two experiments suggest that participants were able to identify balance shifting patterns for on-surface and off-surface scenarios. Even if the participants were engaged in parallel tasks, the patterns could be distinguished within a few attempts.

We observed that participants sometimes confused *FH* and *B* when they performed the action too quickly. Participants' feedback suggested that they may need more time to learn the static balance patterns than the time provided to them in the experiments. Nevertheless, the Glissade prototype can provide at least two static patterns (*i.e.*, *FH* and *BH*) even for novice users.

All participants agreed that the balance shifting feedback of the dynamic patterns was significant and highly distinguishable. Although no statistical difference was found, *BO* seems to be the most distinguishable pattern that requires nearly only one attempt to recognize. This makes *BO* suitable to be used for important interaction events, such as "confirm" or "delete". In addition, since participants could detect the change of balance in *STF* and *STB*, the two patterns could be combined together for continuous input, such as adjusting parameters.

DEMO APPLICATIONS

Here we demonstrate a range of possible scenarios when coupling haptic feedback with pen orientation. At the same time, we illustrate a few new interactions made possible by the application of balance shifting feedback on digital pens.

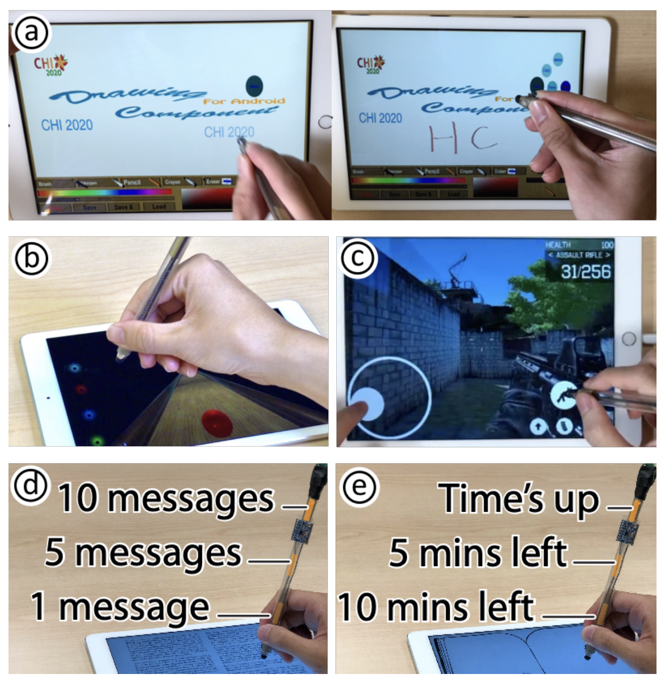

Figure 8. Five demo applications using Glissade: (a) haptic editing board, (b) bowling game, (c) shooting game, (d) the number of unread messages, and (e) countdown timer.

Haptic Editing Board

We propose using Glissade to create a haptic editing board, where the user can sense static and dynamic patterns during auxiliary pen input.

In the editing mode, the pen displays front heavy pattern (*FH*), which allows the user to draw or move objects effortlessly. A user can select a button to open a pie menu, and the pen displays the balanced pattern (*B*). This helps the user understand that the menu mode is activated. The pie menu has two pieces at 0 and 45 degrees, respectively. Each piece consists of two menu items. In total, the pie menu contains four commands, *copy*, *paste*, *delete*, and *adjustment*.

The user rotates the pen to select a piece of the pie menu and then tilts the pen to select the desired menu item. When tilting the pen, the pen also displays the balanced pattern (*B*, 25-30 degrees) for inner items and the back heavy pattern (*BH*, 30-45 degrees) for outer items. The user finishes selecting the command by lifting up the pen.

For *delete* and *copy*, the user selects an object on the screen and then lifts the pen. The object is copied or removed once the pen is lifted up. The pen then displays the front heavy pattern (*FH*), informing the user the menu mode has ended.

For *paste*, after the pen is lifted, the pen stays in the back heavy status (*BH*) to constantly remind the user that the paste operation has not been completed. The user pastes the copied item by landing the pen tip at a desired location and then lifting up the pen again. After that, the pen switches back to the front heavy status.

As for *adjustment*, after the pen is lifted, the pen displays a balance oscillation (*BO*) to inform the user. The user starts adjusting the saturation of pen stroke by tilting the pen inmidair. During the adjustment, the user can feel the *STF* pattern for the saturation value. The user finally completes the adjustment by pressing the pen tip on the screen and receives the front heavy pattern (*FH*) again.

Realism in Games

Like prior works using balance shifting feedback to enhance virtual reality experience [46], Glissade also enables new interactions in gaming for surface computing.

In a bowling game, for example, a more back heavy balance simulates a heavier ball. Furthermore, in a game where the user bowls by swinging the balance-shifting digital pen, shifting the moving mass downwards with the swing creates a haptic sense of throwing the ball (*STF*). In a shooting game, the balance can simulate the amount of ammunition left in a gun. The balance becomes slightly more front heavy whenever a shot is made in the game. To reload, the player holds down the reload button and rotates the balance-shifting digital pen by 45 degrees, while the pen becomes more back heavy matching the rotation.

Haptic Notifications

Aside from expressing the current state of the pen, static balance patterns can be used to convey long-duration system information, owing to the fact that the feedback causes little annoyance even when perpetuated over long periods. For example, when reading a document, the balance of the pens can express unread messages to avoid interference by the message window. Front heavy balance (*FH*) can be used to represent no message while back heavy balance (*BH*) can represent a certain number of messages, determined by the user.

In addition, we have designed a countdown timer that can operate in the background so that the user can realize the time and focus on an application. The user can customize the countdown time, which is mapped to the balance of the pen. At the start of the count down, the pen displays the back heavy balance (*BH*). The balance slowly shifts towards the front as the count down progresses until it reaches the front heavy balance (*FH*), indicating that there is no time left.

Preliminary Evaluation

To understand users' experiences of using Glissade, we conducted a preliminary study and recruited 10 participants (4 females) with more than 6 months' experience using digital pens. We asked the participants to experience the five applications in random order with and without balance haptic feedback. Note that in the condition without haptic feedback, Glissade remains in *FH* state at all times. This condition is regarded as the comparison baseline of applications. There was no time limitation for the study, and participants could experience the applications for as long as they desired. After the experience, participants were asked to give qualitative feedback and subjective ratings on a continuous 7-point Likert scale. The subjective rating questions were *"What was your overall enjoyment when experiencing this application with/without the haptic feedback?"* Ratings were made using a continuous numeric scale from 1 to 7, with 1 indicating "strongly disagree" and 7 "strongly agree."

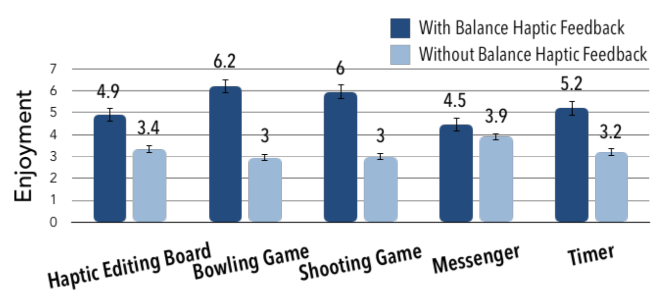

Figure 9. Enjoyment evaluation.

The average enjoyment ratings of applications are shown in Figure 9. The t-test results indicate that user enjoyment was significantly higher in each application with balance haptic feedback (all $p < .05$) except for the messenger application. The rating enhancement was greatest in the two games, bowling and shooting; because participants felt that the feedback makes them fun (P2, P3, P5, P6, P9) and is especially suitable for expressing weight. Moreover, P3 said that *"Applications involving weight are very suitable for this stylus."*, and P8 expressed that *"This feedback can be used to express the weight of instruments."*

On the other hand, participants had mixed feelings for the messenger application. P7 and P8 indicated that the haptic feedback is not more attractive than the audio notification they are familiar with. Also, P4 said that *"I would just look at the screen to find out about the messages."* Nevertheless, P6 and P9 expressed that it is nice that they do not need to look at the screen for information. This is also the reason why users enjoyed the feedback in the timer application.

As for the editing board application, P2, P3, P6, and P7 enjoyed having balance haptic feedback give hints on the layers of the pie menu. P7 also enjoyed the feedback when adjusting saturation. However, she suggested that haptic feedback should be disabled when she needs to concentrate on drawing, as changing balance interferes with drawing.

In summary, balance haptic feedback enhances interaction enjoyment and is best suited for expressing weight.

LIMITATION AND FUTURE WORK

Studies

Our study focused on simple balance patterns to demonstrate the promise of Glissade. The results should be interpreted with reservation when generalizing them to different implementations. Future research will go beyond the discriminability of the balance patterns by investigating deeper questions regarding the perceivability and discrimination threshold values of the kinesthetic feedback. Psychophysical studies such as Just Noticeable Difference (JND) experiments should be conducted carefully to understand (a) the maximum number of the static patterns and (b) other possible combinations of upward and downward mass movements for dynamic patterns.

It is also interesting to more deeply evaluate the effectiveness of the static and dynamic patterns for different purposes, such as gaming or notification applications as we proposed. For example, for gaming, do the patterns increase the realism or enjoyment in games? As for notifications, can the patterns serve as a background notification (*e.g.*, an ambient display)? Understanding these questions will help us to develop versatile applications with Glissade.

Glissade's Hardware

The current Glissade prototype is connected to an external power source and a controller via a wire bundle. As we designed the bundle to be loose and light, there were no user comments concerning the bundle throughout our research, implying that it did not affect participants' ability to feel balance haptic feedback. Nevertheless, to further enhance Glissade's mobility, the wire can be removed by integrating into the pen a small battery and a miniature controller with wireless capabilities.

Exploration of Moment of Inertia

We discovered that the retardation effect caused by the *BH* pattern is only apparent when the pen is moving quickly. Therefore, a more back-heavy balance cannot be used to enhance precision (*e.g.*, help users fine-tune sliders). This also implies that in applications where the stylus is moved quickly (*e.g.*, quick UI tuning) the *FH* pattern will be more appropriate. However, it is possible to use *STB* and *STF* patterns to help guide users in UI tuning. For example, when the user is about to rotate pass the boundary of a tuning region, the *STB* pattern can be used to slow the rotation by increasing the moment of inertia. Applications related to the use of moment of inertia could be created and studied in the future.

Possible Effects on Input Precision

Concerning the impact of balance haptic feedback on input precision, only one participant in our preliminary evaluation mentioned that dynamic balance pattern interferes with drawing. This is likely because the user needs to exert a varying force to maintain precision. Nevertheless, the exact amount of effect should be further studied.

Other Haptic Output Types

In this paper, we focus on addressing kinesthetic force feedback for auxiliary digital pen input. Another important haptic channel, tactile feedback, remains to be explored. For example, vibrotactile feedback has been long-used by prior works on digital pens. Nevertheless, researchers also suggested that tactile feedback should be used *parsimoniously* and should be reserved for status-indication and discovery feedback [22], such as indicating notifications or the boundaries of graphical widgets. For future work, we will explore suitable auxiliary pen input scenarios for vibrotactile feedback and other types of tactile feedback.

Other potential output channels include audio feedback or visual feedback. For example, prior works have proposed using audio [28] or LED light [22] to enhance pen interactions. We believe combining the strengths of each output channel may lead to better experiences in pen-based interactions.

CONCLUSION

We explored coupling balance shifting feedback with the orientation of Glissade: an ungrounded digital pen prototyped to demonstrate the potential of the novel haptic feedback. Six balance patterns, including static and dynamic balance patterns, were designed and evaluated. In two controlled experiments, we separately evaluated the recognizability of the balance patterns as the user changed the altitude of the pen's orientation in a tilting motion and as the user modified the azimuth in a rotating motion. Tests in the experiments were either conducted having the pen be on-surface or off-surface and either with or without a secondary task. The results show that the participants were able to recognize balance patterns with a 94.25% accuracy, which is promising for the utilization of balance shifting feedback in future pen interactions. Finally, we demonstrated five applications to showcase the possibilities of balance shifting feedback and possible interactions when coupling pen orientation with a haptic output. We believe our initial investigations in balance shifting feedback open up a wide range of possibilities for not only auxiliary pen input but also a wide range of potential applications for surface computing.

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