# HaptiStylus: A Novel Stylus for Conveying Movement and Rotational Torque Effects

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**The HaptiStylus utilizes vibrotactile and inertial haptic effects to enrich stylus-based interaction on mobile devices. Psychophysical experimental results and practical application use-case studies show that the proposed device can effectively convey movement and rotational torque information to users.**

A growing set of mobile applications and games use stylus-based input for manipulating and interacting with virtual objects. Despite their popularity as input devices, the styluses currently on the market are passive instruments that were primarily designed for writing and pointing on mobile devices. Because of its inability to support feedback, stylus-based interaction has not reached its potential. (See the "Related Work in Haptic Styluses" for more details.) To address this shortcoming, we designed an active stylus that is capable of creating two tactile effects (movement and rotational torque effects) in an effort to enrich stylus-based interaction.

Our HaptiStylus design is equipped with two vibration motors positioned at the ends of its casing. Asynchronous actuation of these motors results in a sensory illusion known as *apparent tactile motion*.[1] With an appropriate combination of stimulus duration and interstimulus onset intervals (ISOIs) of the vibration actuators, we can produce a movement effect along the body of the stylus. A high-torque-rated DC motor, positioned underneath the fingers, also lets us create a sense of clockwise and counterclockwise rotation. Powering up the DC motor creates torque on the casing of the stylus. When the voltage pulse is cut off, the motor produces reaction torque in the opposite direction. In a previous work, we showed that the torque created during start-up dominates the reaction torque and creates a sense of rotation in the intended direction.[2] Here, we further investigate the effects of the input waveform patterns on the torque created by the motor and the perceived sense of rotation.

In this article, we report detailed results from three psychophysical experiments that explore the effects of actuation timing and waveform on the perception of movement and rotational torque effects. Specifically, we explore the effects of the duration of actuation and ISOIs on the movement effect, and we look at the onset/offset durations and input waveform patterns on the rotational torque effect. In addition, we report the results from our assessment of a haptic stylus game we designed to take advantage of the proposed haptic effects. We carried out this assessment using a more compact version of our stylus (HaptiStylus 2.0), which we fitted with a Bluetooth module for communication and an active stylus tip to enable fine-grained tracking on a digitizing tablet. The results of three psychophysical experiments show that, with carefully selected parameters, we can create highly perceptible movement and rotational torque effects. We did so, not only in a targeted perception experiment, but also in an immersive game where the users' primary focus was on the game dynamics rather than the perceiving effects.

## HaptiStylus Design

The HaptiStylus consists of a plastic cylindrical casing and three physical actuators: one DC motor

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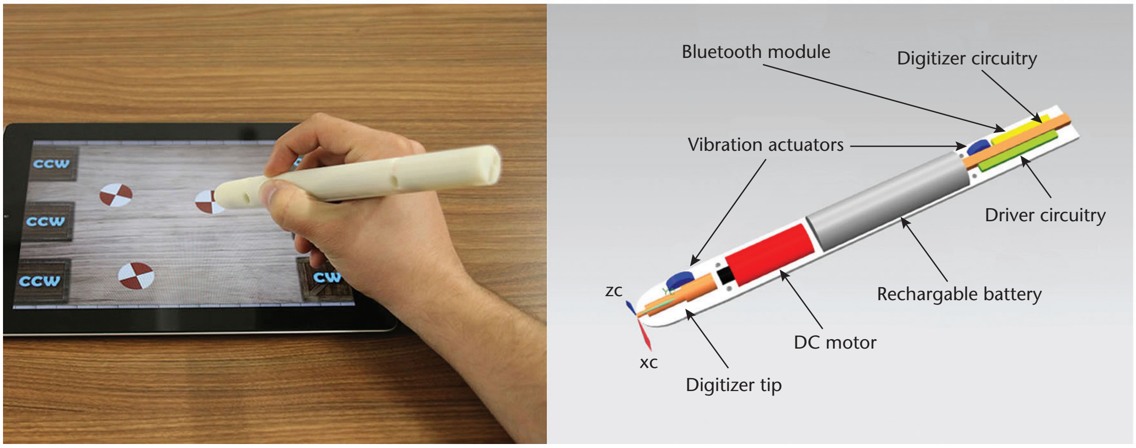
**(a)**




**(b)**

**Figure 1. HaptiStylus components. (a) HaptiStylus 1.0 is a low-cost prototype that doesn't include circuitry inside. (b) HaptiStylus 2.0 is a standalone device with an embedded digitizing stylus tip, control circuitry for actuators, and a Bluetooth module for wireless communication.**

for creating a sense of rotation, and two vibration actuators for generating movement effect. Figure 1 shows two physical embodiments of our design. The pen in Figure 1a was designed as a low-cost prototype that doesn't include circuitry inside, whereas the model in Figure 1b was designed as a standalone device with an embedded digitizing stylus tip, control circuitry for actuators, and a Bluetooth module for wireless communication. The first design helped us evaluate the effectiveness of our approach for generating movement and rotational torque effects. Using the second design, we have been able to further verify our approach in a practical computer game setting. The second design was also used to investigate how the perception of rotational torque effect is influenced by the shape of the waveform that drives the actuators.

Table 1 compares the physical components and specifications of the two HaptiStylus designs. We utilize two coin-type eccentric rotating mass (ERM) actuators to create a movement effect through the stylus. The ERM actuators are compact and lightweight and have a larger frequency and amplitude bandwidth than some other vibration actuators. The actuators are placed close to the end of the stylus (see Figure 1). We used specialized haptic drivers to improve the performance of the vibration actuators. The drivers offer a shorter start-up duration (0.1 ms) using only a single-ended pulse width modulation (PWM) input signal. The use of specialized driver circuits proved to be critical for achieving the targeted effects.

**Table 1. Physical components and specifications of both HaptiStylus designs.**

| Components | HaptiStylus 1.0 | HaptiStylus 2.0 |
|---|---|---|
| Haptic driver | DRV 8601, TI | DRV 2603, TI |
| DC motor | Generic | Re-max 13, Maxon |
| DC motor driver | L293D, ST | DRV 8835, TI |
| Microcontroller | AT tiny 2313-PDIP | AT tiny 2313-QFN |
| Communication | Wired | Bluetooth |
| Dimensions | 30 mm, $L$ = 170 mm | 18.5 mm, $L$ = 192 mm |

To create the rotational torque effect, we used a high-torque rated DC motor. The DC motor is positioned to coincide with the position of the

## Related Work in Haptic Styluses

The literature includes a few studies about creating tactile haptic effects using styluses. Johnny Lee and his colleagues developed the first haptic stylus to produce reaction forces along its longitudinal axis by means of a solenoid actuator at the tip.[1] Ki-Uk Kyung and Jun-Young Lee designed Ubi-Pen, which conveys vibration cues to the user via a single vibration motor, and texture information at the fingertip using an embedded pin array.[2] Later, Kyung and his colleagues miniaturized this pen by removing the embedded pin array.[3] They also developed a GUI on a touchscreen to convey vibrotactile haptic feedback to users via a single linear actuator for user events such as a button click, icon/file pickup, drag-and-drop operation, window resizing and scrolling, text highlighting, and menu movement and selection. Sho Kamuro and his colleagues developed an ungrounded stylus to convey force feedback to users without the use of mechanical linkages.[4] Götz Wintergerst and his colleagues proposed a stylus, with a magnetically operated brake at the tip, to produce haptic effects by controlling the friction between the tip and a display surface.[5] Anusha Withana and his colleagues developed a haptic stylus that dynamically changes its effective length to create an illusion of penetrating a display surface.[6] Ivan Poupyrev and his colleagues explored the benefits of using vibrotactile haptic feedback with a touchscreen in pen-based interactions.[7] They placed four piezo actuators at the corners of a pen-based touch display in between the LCD and the protective glass panel, and they conveyed vibrotactile haptic feedback to users in varying amplitude and frequency. The results of their user study showed that the subjects preferred haptic feedback when it was combined with an active gesture, such as in dragging a slider or highlighting a text using a pen interface. Our work complements this body of work by focusing on a different set of haptic effects: movement and rotational effects.

The haptic movement effect, or creating a tactile illusion of continuous motion, was investigated first by Carl Sherrick and Ronald Rogers via two vibration motors separated by a specific distance and placed on the skin of the user's thigh.[8] They adjusted the stimulus duration and the delay between the actuation times to create an effect of a traveling haptic stimulus. Hong Tan and Alex Pentland developed a wearable tactile chair equipped with vibration motors to transmit static lines and 2D geometric patterns onto the user's back.[9] Ali Israr and Ivan Poupyrev proposed an algorithm to create 2D dynamic haptic effects on the back of a user sitting on a chair, using a matrix of vibration actuators.[10] In another line of work, Israr and Poupyrev investigated the control parameter space for producing reliable continuous moving patterns on the forearm and back via a haptic movement effect.[11] The results of that study showed that the ISOI space for the forearm was influenced by both the motion direction and spacing of the actuators, whereas the ISOI space for the back was affected only by the direction of actuation. Sang-Youn Kim and his colleagues created the sensation of a traveling wave between two vibration actuators embedded in a cell phone by adjusting the magnitude and timing of the actuators.[12] Soo-Chul Lim and his colleagues used frequency modulation to create a haptic movement effect between two hands.[13] Our work explores the use of the haptic movement effect with a pen-based interface that can be used with a tablet or a mobile device. In our stylus, the actuators do not come in direct contact with the skin, and the vibrations are transmitted indirectly through the stylus casing.

Compared with the haptic movement effect, the haptic rotational torque effect has been investigated less in the literature. Kyle Winfree and his colleagues developed iTorqU, an ungrounded handheld device, to

fingers holding the stylus. Our preliminary studies showed that using a specialized driver to control the DC motor is also critical for creating the targeted haptic feedback. Hence, we used special-purpose motor drivers for both designs.

## Generating Haptic Effects

The HaptiStylus can generate two haptic effects: up-and-down movement along the stylus and rotational torque about the long axis of the stylus.

### *Movement Effect*

We achieve the up-and-down movement effect by actuating the two vibration motors while preserving a carefully selected delay between their actuation times. Carl Sherrick and Ronald Rogers observed that actuating two vibration motors placed in close proximity to the skin leads to one of three sensations, depending on the delay between the actuators' start-up times.[1] In particular, depending on this delay, defined as the interstimulus onset interval (ISOI), participants perceive either a single stationary target, two discrete stationary targets, or a single moving target, as shown in Figure 2. When the ISOI is small, it leads to the perception of a single and stationary stimulus (Figure 2a). If the ISOI value is large, it leads to the perception of two discrete stimuli near the actuators (Figure 2b). Using a set of carefully selected ISOI values, it is possible to create the sensation of a stimulus traveling from one vibration motor to the other (Figure 2c).

Earlier studies on the haptic movement effect have also focused on identifying optimal stimuli create directional torque feedback via a flywheel inside a two-axis actuated gimbal.[14] Lope Ben Porquis and his colleagues created a torque illusion via suction by using a vacuum-driven interface embedded in a stylus.[15] Using a rotating flywheel, Tomohiro Amemiya and Hiroaki Gomi conveyed directional torque feedback through a mobile device.[16] Unlike these approaches, we simply use consecutive torque pulses via a DC motor attached to the casing of our pen-based stylus to generate a perceptual sense of bidirectional rotation.

To our knowledge, applying the proposed haptic movement and rotation effects to a pen-based interface is new. Although the haptic movement effect concept is not new, and it has been applied to the other parts of the body, such as the forearm and back, the haptic rotation effect is completely new. Moreover, earlier pen-based interfaces with haptic feedback focused on creating haptic effects for 2D GUI events (such as button clicks, drag-and-drop operations, and menu selection). However, the proposed stylus with haptic effects opens new avenues for 3D haptic interaction because it includes multiple actuators along its long axis.

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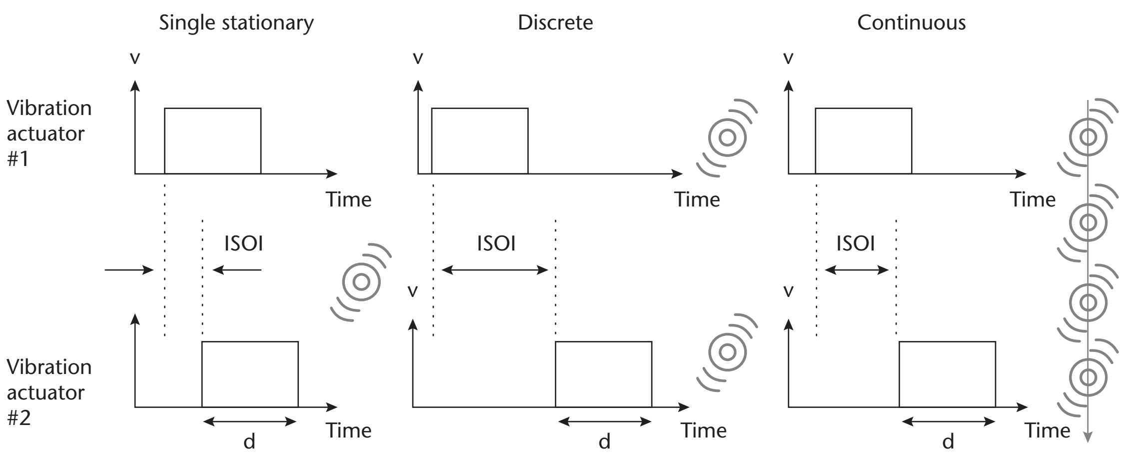


**Figure 2. Interstimulus onset interval (ISOI) effect on apparent tactile motion. Depending on the stimuli duration (d) and the delay between the actuators' start-up times, one of three sensations can be produced: single stationary, discrete, or continuous.**

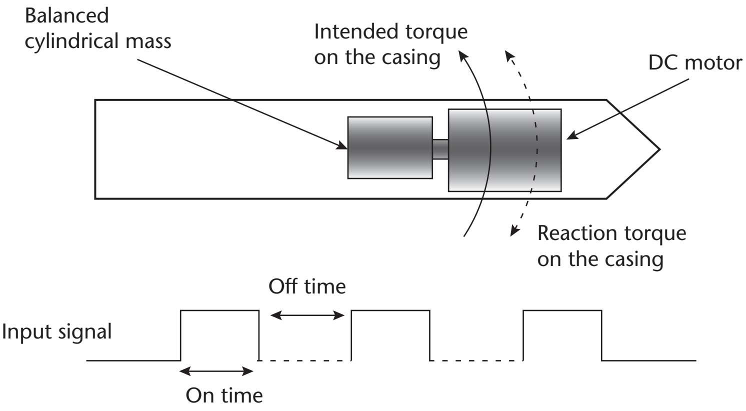


**Figure 3. Rotational torque effect. When the motor is turned on, it generates torque along the intended direction, and when it is powered off, reaction torque is generated on the casing. The HaptiStylus 1.0 design used a balanced cylindrical mass to achieve a greater amount of intended torque.**

duration and ISOI values, but only on sensations through the forearm and back.[3] To our knowledge, our work is the first to investigate the perception of tactile movement on a stylus through the human hand and fingers.

### *Rotational Torque Effect*

Unlike torque feedback devices, a stylus is an ungrounded apparatus, so it is difficult to generate a torque feedback using conventional actuators. Instead, we attempt to induce a sensation of rotation by powering the DC motor through discrete pulses. This creates a short, but perceivable sensation of rotation along the pen's axis by slightly stretching the finger pads (see Figure 3).

The phenomenon that leads to the rotational torque effect is closely related to what happens when a DC motor is powered up. When a DC motor is first powered up, the rotor experiences nonzero angular acceleration until it reaches a terminal angular velocity $\omega_{max}$ (during the on state). This nonzero acceleration causes a corresponding torque $\tau$ in the motor casing in the reverse direction, which approaches zero as the angular velocity approaches $\omega_{max}$. When the motor is powered off (during the off state), a reaction torque is generated in the opposite direction. Generating successive pulses with a carefully selected frequency and duration creates a sense of rotation that is perceivable by the users.

Another parameter that affects the perception of rotation is the shape of the waveform that drives the DC motor. Based on this observation, which became evident in our preliminary experiments, we designed and conducted a controlled psychophysical experiment to compare three alternative waveforms.

## Experimental Results

For each tactile effect, we conducted separate psychophysical experiments to determine effective values of the stimulus parameters. The experimental methods and procedures for the experiments were the same. HaptiStylus 1.0 was used for the first two experiments, which involved three separate groups of 10 participants. The participants did not have any known sensory impairments and were all right handed. During the experiments, the participants used their right hand to hold the stylus and their left hand to enter their responses by pressing the keys on a keyboard. The participants sat comfortably on a chair facing the computer screen displaying the experimental protocol and put on headphones that played white noise to block auditory cues. In the second experiment, which used HaptiStylus 2.0, we used a visual barrier to prevent the participants from seeing their hand and the stylus.

### *Experiment 1: Haptic Movement Effect*

The goal of the first experiment was to determine the effective stimulus duration and ISOI values for the haptic movement effect. Based on our preliminary studies, we selected five values—50, 100, 200, 300, and 400 ms—for the stimulus duration and ISOI. The experiment consisted of 500 trials: 50 trials (5 stimulus durations × 5 ISOIs × 2 directions) with 10 repetitions for each trial. Ten people participated in the study (five females and five males, with an average age of 24 ± 2). The participants completed the experiment in two sessions with a three-hour break between the sessions. Each session took no more than 20 to 25 minutes. The participants were asked to characterize the tactile stimuli created by the vibration motors as either single stationary, discrete, or continuous for each trial. To eliminate any bias during the experiment, the trials in each session were randomized. Before each session, a training session was administered, during which all possible combinations of the parameter values were presented.

Figure 4 shows the results of the first experiment based on the average responses of the participants for two directions of movement (from the tip to the end of the stylus or vice versa). The graphs show the effect of stimulus duration and ISOI values on the perception of vibrotactile stimuli. The combined plot in Figure 4d clearly illustrates the three perceived effects by the participants: the bottom left region represents single stationary, the top left region represents discrete, and the middle right region represents continuous.

We investigated the effects of stimulus duration, ISOI, and the direction of tactile movement on the

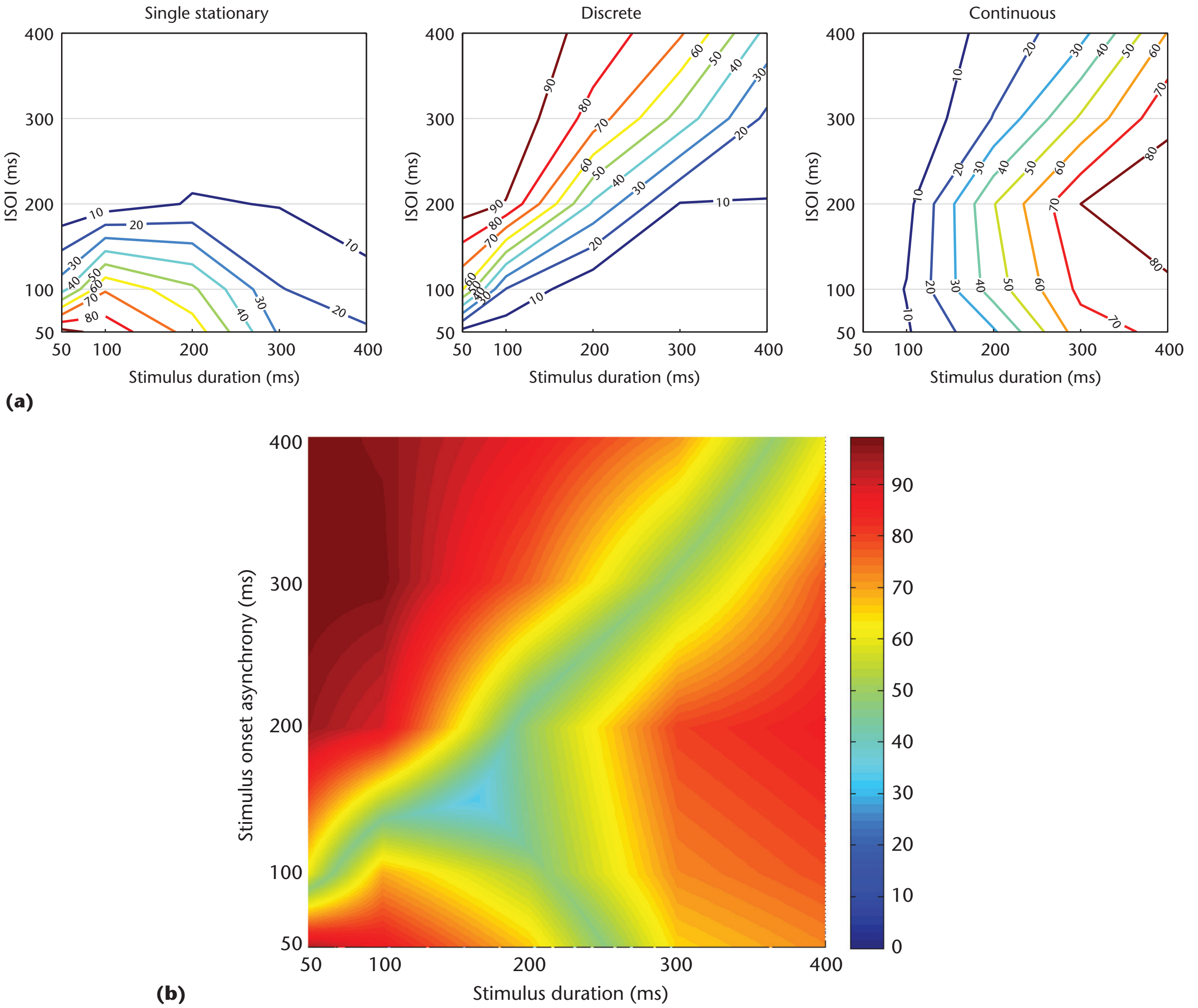


**Figure 4. Movement effect. Mean percentage of votes for two directions of movement (from the tip to the end of the stylus or vice versa). (a) The contour graphs display the percentage of the votes given by users (single stationary, discrete, and continuous) for combinations of various ISOI and stimulus duration values. (b) We combined all three plots to show the rating of the most dominant effect at each point in terms of percentages. The valleys in the combined plot clearly divide the space into three distinct regions corresponding to distinct effects.**

perception of the three possible cases. The participants' responses were analyzed with a three-way repeated measures analysis of variance (ANOVA), and the significance level of $\alpha = 0.05$ was used throughout the analysis. Our analysis shows that the duration of vibration stimulus is a significant factor ($F(4, 36) = 102.64$, $p < 0.05$) for perceiving the movement effect. Results suggested that the perception of the tactile movement effect is higher as the duration of stimulus increases ($p < 0.05$). The ANOVA also suggested that ISOI was a significant factor on the perception of the movement effect ($F(4, 36) = 7.18$, $p < 0.05$]. Paired $t$-tests and Figure 4 suggest that the ISOI values between 50 and 200 ms were perceived as continuous stimuli. The direction of the tactile movement as a third parameter had no effect on the perception of the tactile movement affect ($F(1, 9) = 0.03$, $p = 0.86$). Thus, the results of the analysis show that stimulus duration and ISOI are effective parameters on perceiving the movement effect, whereas the direction of movement has no effect.

The results of the first experiment also revealed that the effective parameter values for obtaining apparent tactile motion in a handheld stylus differ from those reported in earlier studies performed on the forearm and back.[3] This result can be explained by the differences in the sensitivities of the hand, fingertips, forearm, and back.

### *Experiment 2: Rotational Torque Effect*

The goal of the second experiment was to deter-

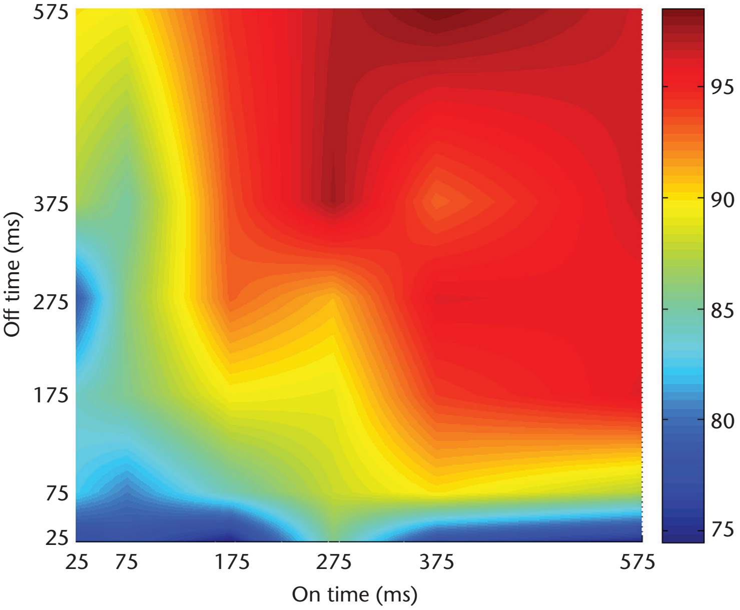


**Figure 5. Rotational torque effect. Mean percentage of votes for two directions of rotational torque: the results of clockwise and counterclockwise trials have been combined.**

mine effective values of on and off durations of the input voltage pulses when producing the haptic rotational torque effect. Based on our preliminary studies, we selected six different values—25, 75, 175, 275, 375, and 575 ms—for the on and off durations. Across the long axis of the stylus, we delivered clockwise and counterclockwise rotational torque directions to the participants during the experiment. The experiment consisted of a total of 720 trials: 72 trials (6 onset × 6 offset × 2 directions) with 10 repetitions for each trial. Ten people participated in the experiment (six females and four males, with an average age of 24 ± 3). The participants completed the experiment in three sessions with a two-hour break between the sessions, and each session took no more than 20 to 25 minutes. In each trial, the participants were asked to identify the direction of rotational torque as clockwise or counterclockwise. Before starting each session, a training session was administered, exposing the participants to all possible combinations of the parameter values.

Figure 5 shows the effect of onset and offset durations on the perception of rotational torque effect in the second experiment. On the graph, the color diagram represents the percentage agreement between the intended and perceived direction of rotational torque by the participants. We performed a three-way repeated measures ANOVA to investigate the effects of on duration, off duration, and motor polarity (used to set the intended direction of torque) on the direction perceived by the participants. A significance level of $\alpha = 0.05$ was used throughout the analysis. The results suggest that both on and off durations significantly affect the perceived direction of rotational torque ($F(5, 45) = 4.49$, $p < 0.05$ and $F(5, 45) = 13.32$, $p < 0.05$, respectively). Figure 5 shows that the participants identified the direction of rotational torque more successfully with longer on and off durations. The ANOVA also suggest that participants perceived the rotational torque in the intended direction ($F(5, 45) = 0.03$, $p = 0.86$).

### *Experiment 3: Waveform User Study*

The haptic rotational torque effect is conveyed using square-shaped input pulses. In the third experiment, we investigate how input waveform patterns influence the perception of the rotational torque effect. Based on our preliminary studies,[2] we selected three input voltage waveforms for this purpose: square wave, square wave with an increasing ramp during the on duration, and square wave with a decreasing ramp during the on duration (see Figure 6).

The same experimental procedures were applied to the participants as in the second experiment. There were 10 participants (five female and five males, with an average age of 25 ± 2). We selected three different values—50, 200, and 350 ms—for the on and off durations based on our preliminary studies.[2] There were a total of 180 trials in this experiment: 18 trials (3 on durations × 3 off durations × 2 directions of rotational torque) with 10 repetitions of each trial. The participants completed the experiment in two sessions on the same day, and each session took no more than 20 minutes. In each trial, the participants were asked to identify the torque produced through the casing as either clockwise or counterclockwise with respect to the long axis of the stylus. The trials in each session were randomized to eliminate any bias. Before starting the experiment, the participants went through a training session, exposing them to all possible combinations of the duration values and waveform patterns.

Figure 7 shows the effect of input voltage waveform on the perception of the direction of rotational torque. In each plot, the red region represents the parameter space in which the participants perceived the correct direction of the rotational torque. We also analyzed the participants' responses with a one-way repeated measures ANOVA. A significance level of $\alpha = 0.05$ was used throughout the analysis. The ANOVA results suggest that the waveform of the input voltage significantly affects the perception of rotational torque ($F(2, 26) = 41.96$, $p < 0.05$). The results also show that participants identified the direction of

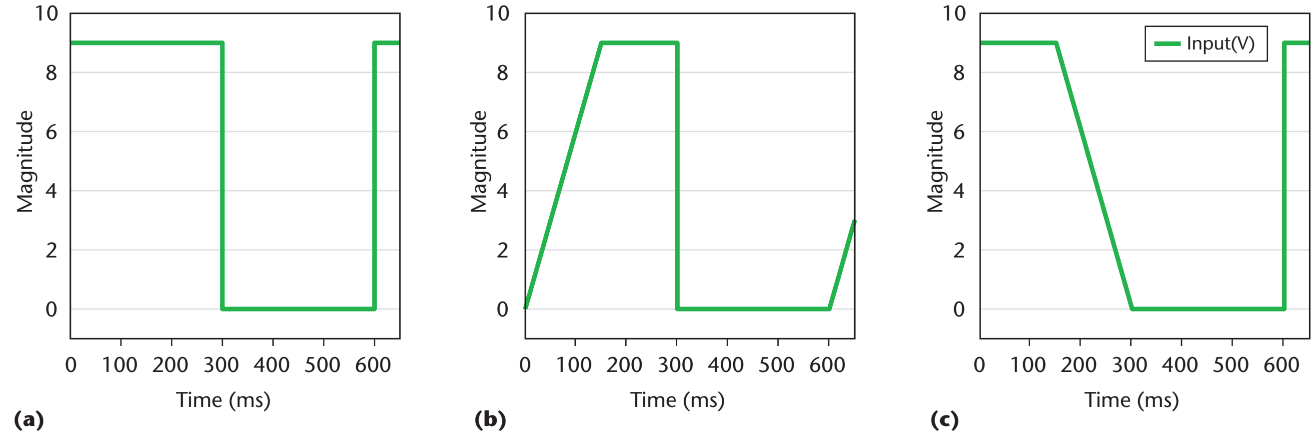


**Figure 6. Waveform study. For the third experiment, input waveform patterns for rotational torque effect, we used (a) a square wave, (b) a square wave with an increasing ramp during the on duration, and (c) a square wave with a decreasing ramp during the on duration.**

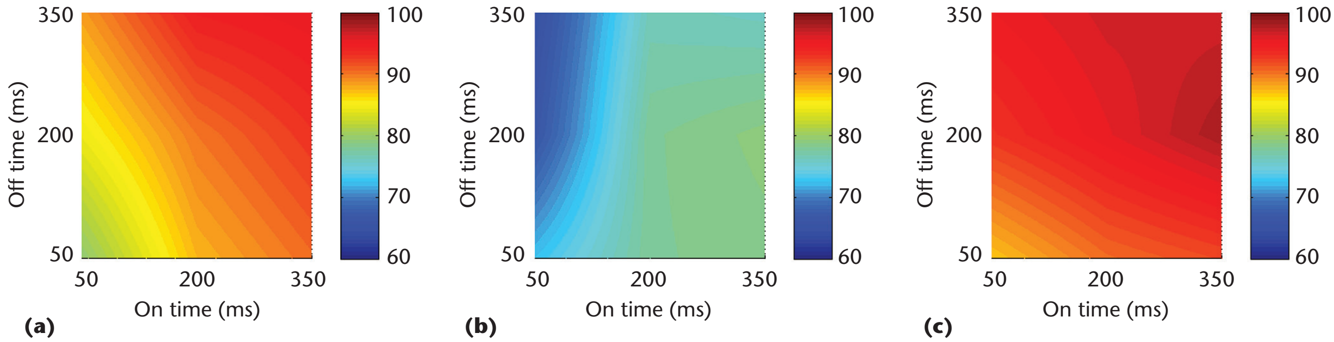


**Figure 7. Waveform study results. The percentages for the participants that correctly identified the (a) square-shaped, (b) increasing, and (c) decreasing waveform patterns.**

rotational torque more successfully when a square wave signal with a decreasing ramp during the on duration interval was applied to the motor.

The results of the third experiment clearly suggest that, in addition to the on and off durations, the waveform is another significant factor on the perception of rotational torque. For example, at 200 ms on and off durations, the participants perceived the direction 90, 78, and 95.5 percent of the time for the three waveforms, respectively (see Figure 7). The increase from 90 to 95.5 percent can be explained by the observation that a gradual offset of voltage spreads the torque effects in the reverse direction over time and results in smaller differences in torque per unit time. We anticipate that the torque perceived in the undesired direction becomes less noticeable as the differences fall below the just noticeable difference (JND)., but this topic obviously requires further investigation.

## Practical Use Cases

To illustrate the vast potential of the movement and rotation haptic effects in practical applications, we designed two mockup demonstrations and an interactive stylus-based game. The mockup demonstrations are supported by a supplementary video, and the discussion of the stylus-based game is supported by a rigorous user study that measures the degree to which the effects in question can be successfully rendered and perceived by the users.

### Mockup Demonstrations

Our mockup demonstrations are available on the *CG&A* YouTube channel (available at https://youtu.be/4qn0DfmhVko) and as Web extras in the IEEE Computer Society Digital Library. The videos illustrate how our technology could potentially be embedded into two real-world applications to build engaging interfaces. The first application concerns a serious information visualization problem, and the second is an interactive mobile game with rich graphical and interactive elements.

**Information Visualization.** Today, we mostly use the visual channel to extract information from data. However, when the number of dimensions in a dataset is large and/or it needs to be represented in connection with other datasets, purely visual representations typically overwhelm users. An excellent

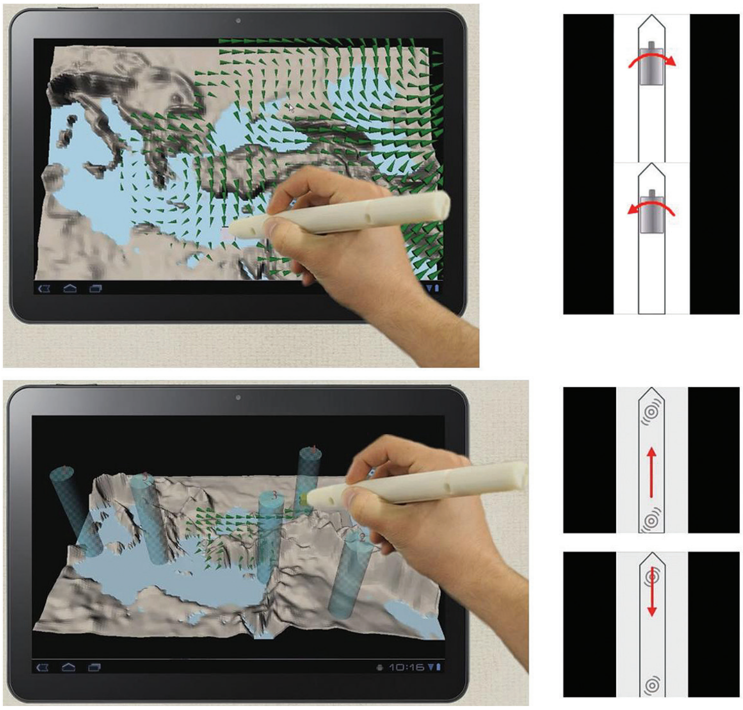

**Figure 8. Climate visualization mockup. Climate visualization requires conveying multidimensional information. Using the proposed stylus, we could convey the direction of circulation and the rise-fall movements of the wind with haptic effects.**

example of this is climate visualization. Climate data typically consists of values for temperature, humidity, wind intensity and direction, precipitation, and cloud water for a set of grid points in the atmosphere. Patterns in and relationships among these variables need to be examined in order for climate phenomena to be understood. Because the data is complex and includes numerous dimensions, different parameters are typically shown on separate maps, which means any interpretation of the data requires the integration of information from multiple maps. This may be especially difficult for nonexperts.

Using the proposed stylus, we could communicate some climate information through the haptic channel to alleviate the perceptual and cognitive load on the user (see Figure 8). For example, vorticity is a force defined as the curl of the wind velocity, and it represents the amount of circulation or rotation. The haptic rotation effect can help communicate to the user the direction of this circulation. Moreover, the vorticity makes the wind rise or fall as a result of the air circulation, which can also be conveyed via the haptic movement effect. In this fashion, haptic feedback may improve the discovery, learning, and retention of cause-and-effect relationships in multidimensional climate data.[4]

**Mobile Gaming.** With the widespread introduction of mobile devices, mobile gaming has become increasingly more sophisticated. With the integration of rich haptic feedback on mobile devices, these games will become more immersive, enjoyable, and engaging. As an example, we suggest the use of haptic feedback in a mock-up dentist game designed for kids. The dentist games available on the market are virtual platforms that teach kids about oral health. They typically involve the simulation of various dental procedures (such as cleaning, drilling, brushing, filling, and suction) performed with dental tools. These games are also excellent examples demonstrating the importance of multisensory experiences because it is more fun to play them when the audio is on. Hence, we believe that haptic feedback produced by a stylus can further augment this experience by stimulating the tactile channel. For example, we can show the tactile difference between brushing front, middle, and back teeth as well as using suction in the mouth (see Figure 9). On the other hand, the haptic rotation effect can produce the feeling of drilling or polishing a tooth.

### *Spinning Tops Game*

To further demonstrate the practical utility of the proposed haptic effects, we developed an interactive pen-based game called Spinning Tops using the Game Maker game engine (https://www.yoyogames.com/studio).

As Figure 10 shows, the game involves three tops, spinning at three different speeds and in two directions. There are three boxes on each side of the screen. The boxes on the left and right are labeled CCW and CW, indicating a counterclockwise or clockwise spin, respectively.

The goal of the game is to first identify the spinning direction of each top and then drag and drop it into an open box on each side using visual and haptic cues. The direction of the spin (CCW versus CW) is conveyed to the user via the visual and haptic (rotational torque effect) cues, and the availability of the box (open versus closed) is conveyed only through the haptic movement effect. A box is open (closed) for a drop if there is haptic movement from the distal (proximal) end of the stylus to the proximal (distal) end of the stylus.

We designed three sets of experiments for the Spinning Tops game. We then asked 15 participants (average age of 23 ± 5) to play the games using HaptiStylus 2.0. For this purpose, we selected the most effective parameter values based on the results of the psychophysical experiments.

**Experiment 1.** We first investigated the effect of haptic cues on the perception of spin direction

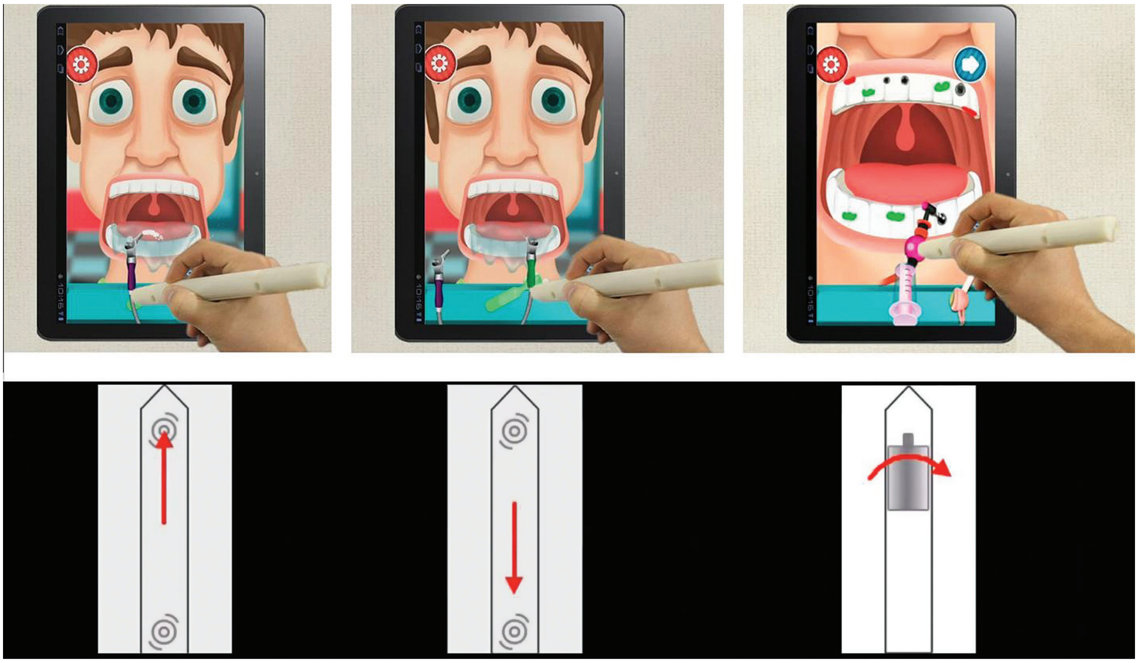

**Figure 9. Mobile dentist game mockup. In this game, the player provides dental care with virtual tools. Haptic effects can enhance the experience of using the tools, such as by simulating the downward movement for a water syringe, the upward movement of a suction tip, or the rotation for a drill.**

and availability of the boxes when the visual cues in the scene are not sufficient for making decisions. For this purpose, the tops were rotated 90 degrees per frame in the visual scene, and the visual scene was updated at 30 frames per second. Because the symmetrical pattern on the surface of the tops repeats itself every 180 degrees, the tops appear to be stationary, and the participants could not differentiate the spin direction.

The experiment was performed under two different sensory conditions:

- No visual and haptic cues (NVH) were available to the participants about the direction of the spin (CCW versus CW) and the availability of the boxes (open versus closed).
- Only haptic cues (OH) were displayed to the participants about the direction of the spin (via haptic rotational torque effect) and the availability of the boxes (via haptic movement effect).

There were 40 trials in this experiment (2 sensory conditions × 2 spin directions × 10 repetitions). The trials were randomized and then displayed to the participants in the same order.

Figures 11a and 11b show the results of the first experiment. The participants made random decisions when there were no visual and haptic cues (NVH condition). The percentage of correct response was 45 ± 13 percent (Figure 11a) and 32 ± 10 percent (Figure 11b) for the spin direction and the availability of the box, respectively. (The expected percentage of correct responses was 50 percent for the spin direction, with one out of two directions, and 33 percent, with one out of three boxes, for the availability of the box.) These values increased to 81 ± 19 percent (Figure 11a) and 65 ± 24 percent (Figure 11b), respectively, when the participants were provided with haptic cues (OH condition). Further analysis with one-way repeated measures ANOVA suggests that the percentage of correct responses under NVH and OH conditions are significantly different ($F(1, 14) = 27.7$, $p < 0.0001$).

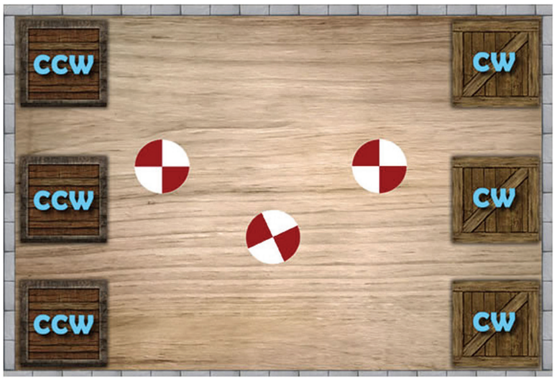


**Figure 10. Screenshot of the Spinning Tops game. Players must drag and drop the spinning tops into the CCW and CW boxes, depending on whether they are spinning in a counterclockwise or clockwise direction, respectively.**

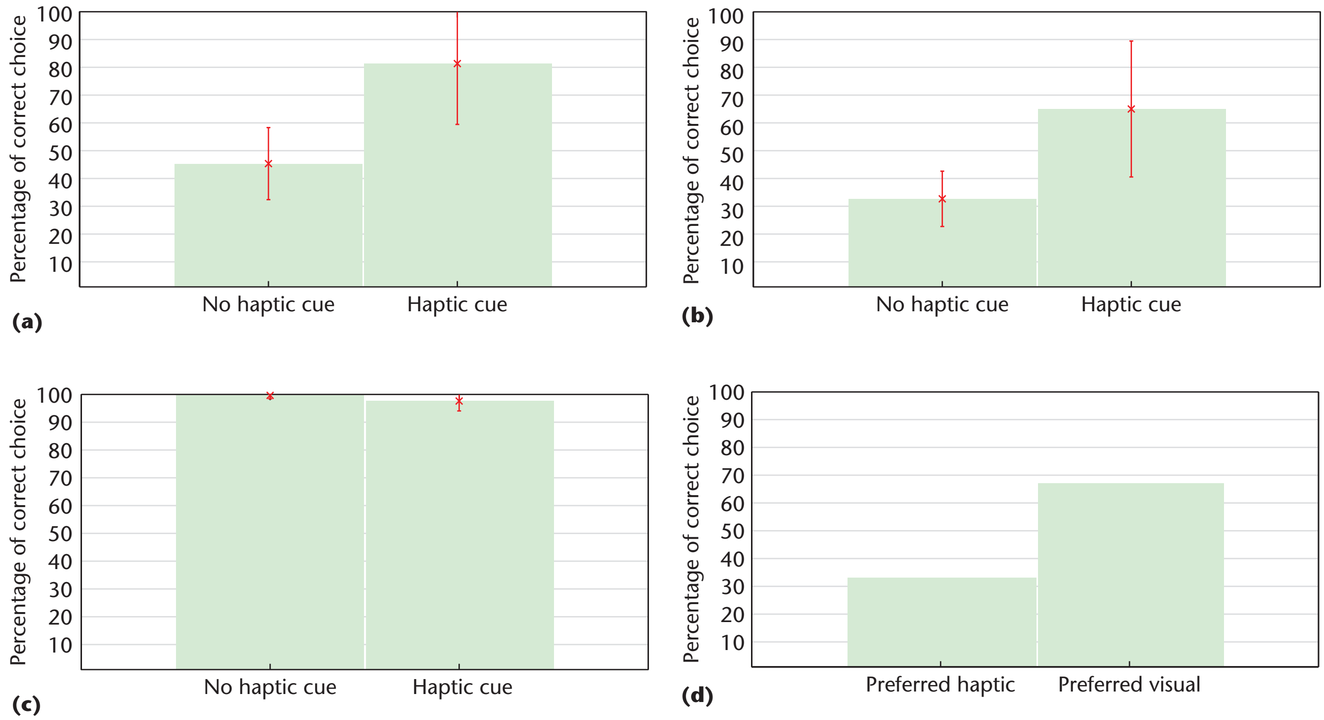


**Figure 11. Spinning Tops game. Percentage of correct choices of participants under various sensory conditions for tactile movement and rotational torque effects: (a) rotational torque effect, (b) movement effect, (c) only visual cues (OV) and both visual and haptic cues (VH), and (d) mismatched visual and haptic cues (MVH).**

**Experiment 2.** Next, we investigated the effect of haptic cues on the perception of spin direction when there are already sufficient visual cues in the scene to make a decision. For this purpose, the tops were rotated at 45 degrees either in the CW or CCW direction, and the visual scene was updated at 30 frames per second. It was straightforward to differentiate the direction of spin by visually inspecting the scene.

The participants played the game under two different sensory conditions:

- Only visual cues (OV) were provided to the participants about the spin direction.
- Both visual and haptic cues (VH) were provided to the participants via the rotational torque effect about the direction of spin.

As Figure 11c shows, the participants were 100 and 98 percent correct in their responses under OV and VH conditions, respectively, and there is no significant difference between these two sensory conditions.

**Experiment 3.** Lastly, we investigated the performance of the participants when there is a mismatch between the visual and haptic cues. For this purpose, the tops were rotated at 45 and 135 degrees per frame in the CW and CCW directions, respectively. When the tops were rotated at 45 (135) degrees per frame, participants visually perceived them as spinning in the CW (CCW) direction or vice versa. During the mismatched visual and haptic condition (MVH), the haptic cues were provided to the participants in the direction opposite of the visually perceived one, causing a disparity between the visual and haptic cues.

As Figure 11d shows, under ambiguous sensory conditions, the participants preferred the visual cues over the haptic ones when making a decision about the direction of rotational torque. Also, a one-way repeated measures ANOVA showed that the VH and MVH conditions differed significantly ($F(1, 14) = 38.7$, $p < 0.0001$).

## Future Work

In our experiments, we explored a comprehensive set of values for parameters that create a sense of rotation across the long axis of the stylus. However, we did not attempt to build a mathematical model of the relationship between the parameters and perception ratings. The challenge in relating input values directly to the perceived sensations lies in the fact that both the input parameters and the sensation ratings are discrete labels; however, they are connected through a time-varying torque signal, which is continuous. Hence, a feasible strategy might involve building a mathematical model of the relationship between input parameters and output torque, as well as the relationship between the torque profiles and the perceived effects. To assess the feasibility of this idea, we collected torque data for combinations of input parameter values by attaching a torque sensor on the stylus casing.[2] Preliminary results from a set of system identification experiments show that it is possible to obtain a mathematical model of the relationship between the input parameters and torque responses of the DC motor. This leaves the task of relating the perceived user sensations to the displayed torque profiles as an interesting piece of future work. This may potentially lead to a framework for inferring optimal actuation parameters.

Another area of future work involves improving the physical and ergonomic characteristics of the stylus. Compared with our original stylus, the HaptiStylus 2.0 design is substantially more compact, but improvements are still needed to achieve the form factor of a regular stylus. This is partly because all the parts we used (the actuators and batteries) were off-the-shelf items. Replacing these with custom-made versions with smaller form factors will likely lead to improvements. An improved form factor is also likely to improve the ergonomic character of the stylus, which deserves further exploration. A possible direction might involve investigating parameters such as stylus length, center of gravity, casing texture, and pen-skin contact area.

Our HaptiStylus design opens up new avenues for exploration in the pen-based computing and haptics communities. We believe that HaptiStylus can be used in a variety of mobile applications including games, entertainment, and education. For example, the movement effect can help communicate to users the injection/discharge of fluids (simulating needle injection in a game), the trajectory of an object moving toward or away from a scene (an approaching fire engine in a video scene), or penetration into a soft object (touching and feeling the softness of organs in a visual scene). Similarly, the rotational torque effect can convey to users the opening and closing of valves and screws or a sense of rotational inertia in spinning and rolling objects (flying an airplane in a game). This list is certainly not exhaustive, but it illustrates the abundance of potential applications.


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