

Frictio: Passive Kinesthetic Force Feedback for Smart Ring Output

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ABSTRACT

Smart rings have a unique form factor suitable for many applications, however, they offer little opportunity to provide the user with natural output. We propose passive kinesthetic force feedback as a novel output method for rotational input on smart rings. With this new output channel, friction force profiles can be designed, programmed, and felt by a user when they rotate the ring. This modality enables new interactions for ring form factors. We demonstrate the potential of this new haptic output method through *Frictio*, a prototype smart ring. In a controlled experiment, we determined the recognizability of six force profiles, including *Hard Stop*, *Ramp-Up*, *Ramp-Down*, *Resistant Force*, *Bump*, and *No Force*. The results showed that participants could distinguish between the force profiles with 94% accuracy. We conclude by presenting a set of novel interaction techniques that *Frictio* enables, and discuss insights and directions for future research.

Author Keywords

Haptics; ring; wearable; passive kinesthetic force feedback

ACM Classification Keywords

H.5.2. [Information interfaces and presentation]: User Interfaces – Haptic I/O

INTRODUCTION

Smart rings have become important peripherals within the ever-growing ecosystem of wearable devices [1]. Unlike smart phones, smart rings support subtle, socially-acceptable, always-available, eyes-free interaction due in large part to their miniature size and form factor. However, given their compact size, input and output capabilities on smart rings are still limited. Existing research with smart rings has primarily focused on leveraging smart rings for input [6, 9, 11, 18-23, 27, 34, 43, 46, 47], with less effort devoted to output. The existing work on ring-based output typically uses light [7, 19, 25, 31], sound [35], vibration [7,

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8, 19, 24, 31, 45], skin drag [17], or poking [35], which require substantial user attention, and is often decoupled from the input mechanism. Haptic force feedback offers the promise of subtle output that is tightly coupled with input, but unfortunately remains unexplored on smart rings.

In this work, we propose passive kinesthetic force feedback as a viable output method for rotational input on smart rings. Smart rings often leverage rotational input, mimicking the natural behaviors often performed with traditional rings [2, 28]. When enhanced with force feedback, such ring rotating behaviors can provide feedback that can be perceived without continuous visual attention. This output not only fits naturally in a ring form factor, but also complements existing smart watch output mechanisms with increased bandwidth and creates opportunities for new interactions. With such an output channel, different friction force profiles can be designed, programmed, and consequently felt by a user whenever they rotate the ring. Depending on the needs of an application, these force profiles can make it harder to rotate the ring or completely lock it in place. Such functionality can be mapped, for example, to the time remaining until wearer's next meeting, offering a convenient, always-available, calendar application (Figure 1).

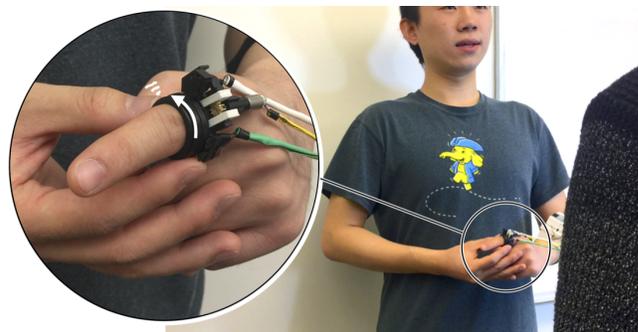


Figure 1. A user chats with his colleague while rotating *Frictio* (without looking at the ring). As the ring exhibits some rotational stiffness, he knows that his next meeting starts soon.

To explore the potential of this output channel, a prototype, *Frictio* [*“Frick-tee-oh”*], was developed using a 3D printed ring, complete with an inner race for wearing, rotatable outer race for rotational input, a rubber brake pad, and a miniature gear motor to drive the brake pad against the outer race (Figure 2). The device detects the rotation of the outer race with an approximate 1° sensing resolution using two Hall

Effect sensors. The strength of the braking force was controlled by adjusting the traveling distance of the brake against the outer race and was monitored using an IR-based proximity sensor.

We evaluated the potential of ring-based passive kinesthetic force feedback in a controlled experiment, where the recognizability of six force profiles, including *Hard Stop*, *Ramp-Up*, *Ramp-Down*, *Resistant Force*, *Bump*, and *No Force*, was determined. These profiles were evaluated under four conditions (i.e., *walking or standing*, and *with or without cognitive load*) to understand how real-world scenarios would affect the perception of force patterns. The results demonstrated that participants could distinguish between the force profiles with 94% accuracy. Preliminary subjective feedback suggested that participants welcomed passive kinesthetic haptic feedback as a useful addition to existing smart ring output. Finally, we developed several example applications to illustrate potential usage scenarios of this novel output channel.

Within this paper, we contribute: the notion of passive kinesthetic force feedback as a new output channel on smart rings, a prototype that is able to render this force, the results of an experiment evaluating the recognizability of six force profiles, and a set of usage scenarios that demonstrate novel interactions using this new modality.

RELATED WORK

This work was inspired by, and extends work on smart ring input and output [36], as well as haptics on 1-D rotary physical controls.

Smart Ring Input

Using the smart ring as an input device has been widely studied by many researchers. A large body of work has focused on utilizing the motion of the ring finger for input [6, 9, 11, 18-23, 27, 34, 43, 46, 47]. For example, LightRing [22] used an IR-based proximity sensor and gyroscope to detect 2D finger movements on a flat surface, while others used an IMU or magnetometer to detect finger motions in a 3D space [18-21, 34, 43, 46]. The tapping motion of the finger on a flat surface was also detected using a ring for text entry [27]. Incorporating an RGB camera, a smart ring was able to capture finger gestures [5] or retrieve contextual information about one's surroundings [26]. Smart rings were also used to detect user activities, such as interacting with mobile devices [41], or to monitor health conditions, including blood oxygen levels [32] or one's pulse [42, 44].

Aside from the unique interactions enabled by smart rings, input on smart rings can be subtle, socially acceptable, always-available, and eyes-free [2, 15, 16, 24, 28]. For example, tapping the ring [24], pinching [16] or flexing the ring finger [13, 28] can draw much less attention to a wearer than interacting with a smartphone or smartwatch, however, input bandwidth is limited with such smart ring-based methods. On the other hand, rotating the ring around the finger is a natural way to provide 1-D input and can be used

for more complex tasks such as menu selection [2, 28]. Ashbrook, et al. found that up to eight discrete targets can be selected by rotating a ring without the need for visual or haptic feedback [2].

Smart Ring Output

In contrast to input, output capabilities on smart rings are far more limited. Due to the small form factor, communicating rich information to users is challenging. A common communication method is to use an LED [7, 19, 25, 31]. For example, Miner et al. [25] suggested that integrating a colored LED within a piece of digital jewelry could alert users about email notifications. Pingu [19] used a RGB LED to visualize finger gestures drawn in mid-air. Ring*U [7] used an LED and vibrotactile feedback to help remote couples feel connected. Ogata et al. [29] enhanced finger expression with anthropomorphic ring. Touchscreens have also been used to convey more complex visual information [15]. Due to the small form factor, however, interacting with a touchscreen on a smart ring poses many usability issues and is often too obtrusive to be viable in many situations.

Of most relevance to the present exploration, vibrotactile feedback has been used on smart rings to provide low bandwidth messages to users [7, 8, 19, 24, 30, 31, 45]. For example, Marti, et al. [24] used vibrotactile feedback as a mechanism to inform users of an incoming call. Pingu [19] vibrated to alert the users about important messages from a coupled smart device. Pradana et al. [31] and Werner et al. [40] used vibrotactile feedback to create a sense of presence for remote couples. Freeman et al. [8] and Yeom et al. [45] used vibrotactile feedback for mid-air hand gestures. Roumen et al. [35] examined light, sound, vibration, poking, and temperature manipulation on a ring. They found that the haptic modalities (vibration, and poking) were among the most noticeable for notifications. As demonstrated by TactoRing [17], dragging a tactor against the skin of the finger can also be used to deliver notifications. This prior work largely focuses on the use of vibration for notifications, or to provide output that is decoupled or unrelated to the user's input. In contrast, Frictio's use of passive haptic feedback can naturally accompany the user's rotational input.

Force Feedback for 1-D Rotary Physical Controls

In contrast to the cutaneous haptic feedback, kinesthetic force feedback in a smart ring form factor has not been previously studied. Within the literature, work with rotary haptic knobs is most relevant [3, 12, 37, 39]. Haptic knobs are computer controlled knobs, developed to simulate conventionally controlled physical knobs, whose profiles are obtained mechanically via springs, detents, or hard stops. Haptic knobs have been used in situations such as within a vehicle, to allow force profiles to be dynamically programmed for different applications [3]. Ha et al.'s [12] device provides haptic feedback, however it was used to aid in the design of dial knobs for a washing machine, radio, and game controller. Snibbe et al. [37] demonstrated the effectiveness of haptic knobs to manipulate digital media such as videos.

Frictio differs from this existing work in that it explores how passive kinesthetic force feedback can be perceived as an output channel within the context of ring-based feedback. Thus, the goal in this work was to develop and study this new feedback mechanism in a smart ring form factor.

FORCE FEEDBACK DESIGN PARAMETERS

There are many options and trade-offs to consider when developing a force feedback system for a ring.

Tactile vs. kinesthetic feedback. Haptic user interfaces encompass both tactile and kinesthetic feedback. Tactile feedback relies on the cutaneous senses and is created by stimulating the mechanoreceptors within the skin. Vibrotactile output from a smartphone or smart watch is an example of tactile feedback. In contrast, kinesthetic force feedback relates to the feeling sensed from muscles, tendons, and joints.

Active vs. passive force feedback. The haptic feedback provided by the device can either be active or passive [33]. Active force feedback induces human motion whereas passive force feedback resists human motion, often through a friction brake [10]. The two types of force feedback provide different interaction opportunities – for instance, active feedback may be more suitable for providing notifications or other ‘asynchronous’ information [17], whereas passive feedback may be more suited for providing output that directly relates to the user’s input. Frictio focuses on passive kinesthetic force feedback.

Fidelity. The hardware implementation influences the fidelity of the generated force feedback. Motors from commercial haptic devices can generate a rich variety of force profiles, such as detents, material softness, elasticity, or rigidity [3, 12]. The trade-offs, however, lie in the complexity of the system and its bulkiness. Implementation can be challenging because existing technologies are designed for larger devices, making them unsuitable for finger-worn devices. Our approach is similar to prior work [10, 17], in that we created a low-fidelity prototype that supports fundamental features (e.g., generating the friction force on the outer race).

Throughout the design and implementation process of Frictio, we sought to carefully balance the benefits of different types of haptic feedback with the technical possibilities offered by the technology available today and prior research that has been conducted. As such, the current design allows the device to be compact, enables for a validation of the effectiveness of the proposed concept and demonstrates technical feasibility, while exploring a new frontier in finger-based feedback that is afforded by passive kinesthetic force feedback.

FRICTIO PROTOTYPE

The prototype is composed of a ring, a braking system, and necessary electronics (Figure 2). The ring was 3D printed using GPBK02¹ resin on a Formlabs2 printer. It has an outer race that can be rotated in either direction. A small DC gear motor (TGPP06-D²), in combination with a rack and pinion gear mechanism was used to move a rubber brake in contact with the outer race. When the brake is engaged, users feel a high friction force resisting their rotation. The gear motor provided sufficient torque to lock the outer race into a full stop position. The gear motor was controlled using a TB6612FNG³ Motor Driver Carrier that was connected to an Arduino Micro board and communicated with a MacBook Pro laptop.

The brake’s rest position is approximately 1 mm above the outer race to ensure the brake can be engaged quickly to minimize latency in providing feedback. The brake moves at a linear speed of 20 mm/s with a minimum distance of approximately 0.1 mm (measured using a high-speed camera). A QRE1113GR⁴ reflective proximity sensor (Figure 2) was used to monitor the brake position during braking and ensure that the brake came back to the rest position when disengaged from the outer race. This provides the system with information about the amount of the braking force based on the distance the brake traveled. Although, a pressure sensor could be used to measure the braking force, the present implementation was sufficient to render many different force profiles and resulted in a smaller form factor.

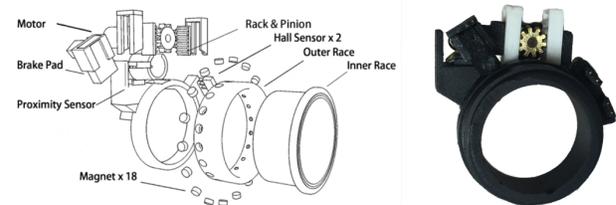


Figure 2. Left: A prototype assembly explosion diagram of Frictio. Right: The front view of Frictio.

The rotational angle of the outer race was tracked using magnets and two A1324⁵ Linear Hall Effect sensors. Eighteen neodymium disc magnets (2 mm diameter × 1 mm height) were placed inside the outer race and were evenly spaced 20° apart from each other with alternating magnetic poles. With this setup, the sensor readings achieve maximum (positive pole) or minimum values (negative pole) whenever a magnet is directly underneath them. The Hall Effect sensors were positioned such that they were 30° apart relative to the center of the ring, allowing for the detection of the rotation direction (Figure 3). The outer race’s angular displacement within the two adjacent magnets was inferred using linear interpolation of the peak and valley values. This enabled Frictio to achieve approximately 1° sensing

¹ www.formlabs.com/store/us/form-2/buy-materials/?RS-F2-GPBK-02=1

² www.ttmotor.com/products/show.php?sid=212&id=123

³ www.sparkfun.com/products/9457

⁴ www.pololu.com/file/0J117/QRE1113GR.pdf

⁵ www.allegromicro.com/~media/Files/Datasheets/A1324-5-6-Datasheet.ashx

resolution. An Arduino Uno sampled the analog values of the Hall Effect sensors at 1000 Hz.

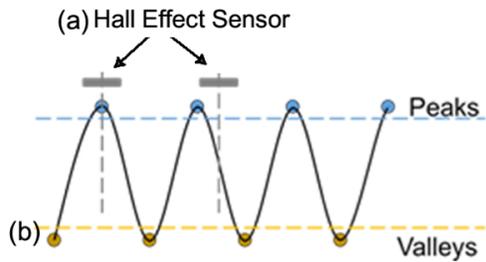
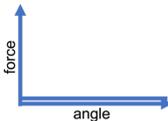


Figure 3. (a) Two Hall Effect sensors are used to detect rotational displacement and direction. (b) The Hall Effect sensor signal.

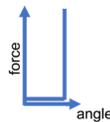
FORCE PROFILES

To demonstrate the capabilities of this new output channel, five force profiles were designed and implemented. The profiles were triggered based on rotation angle. Once triggered, the profiles were rendered over rotation angle (*Ramp-Up/Down*), time (*Hard Stop, Resistant Force*), or both (*Bump*). Each force profile was inspired by an existing rotatable object (e.g., soda bottle cap) or mechanical knob.

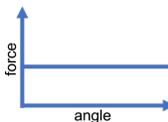
No Force. The outer race is free to rotate without any resistive force applied by the brake. The only force felt by the user is the light friction between the inner and outer race. The resisted torque in this case is ~ 0 Nm.



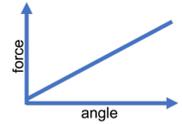
Hard Stop. When the outer race is locked, the ring is unmovable in a certain position. A Hard Stop prevents the ring from being rotated, so it can be triggered after the user rotates the ring a certain number of degrees. This causes the outer race to be immovable by the user. We implemented the Hard Stop by rapidly engaging the brake by running the motor for 50 ms to depress the brake against the outer race, which resists a torque up to 0.06 Nm. After running the motor, the pad stays in place against the outer race to maintain resistance against rotation. In our implementation, the maximum braking force the brake pad can apply to the outer race is 3 N.



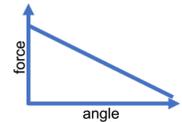
Resistant Force. The Resistant Force represents a force that requires effort from the user to overcome. It falls between the Hard Stop and No Force. Our implementation resists a torque of 0.03 Nm. With the Resistant Force, the outer race can still be rotated, but requires extra effort from a user to overcome the friction force. Rotating the ring allows the user to feel the force and associate it with a certain event. Similar to the Hard Stop, it could be used to deliver specific messages to a user. Different information could be encoded in the braking force, with a light resistant force representing one piece of information, and a stiffer force representing another.



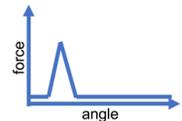
Ramp-Up. The friction force applied to the outer race increases as the ring rotates. Ramp-Up starts at 0° and ends after the outer race was rotated 180° . The peak resisted torque is 0.04 Nm. From the user's perspective, the ring becomes harder to rotate the more the ring is rotated. Similar to the other force profiles, Ramp-Up can be associated with specific events or messages. By changing the slope of the 'ramp', as well as the duration of the ramp, different information can be encoded and conveyed to the user. Alternatively, this profile can be used to assist with fine-grained motor control for continuous input or to simulate the force that would be found while interacting with physical objects, e.g., closing the cap on a soda bottle.



Ramp-Down. Ramp-Down is the opposite of Ramp-Up, whereby the ring becomes progressively easier to rotate. In our implementation, Ramp-Down starts with a resisted torque of 0.04 Nm, and gradually decreases the braking force to that found with the No Force profile as the user rotates the ring. As with Ramp-Up, the slope and duration of the ramp can be modified.



Bump. The outer race stops at the bump, which requires a stronger rotational force from the user to overcome. A haptic bump is distinguishable and can be used to represent certain events. Information can also be encoded through the number or density of the bumps. Additionally, the 'force' of the bump as well as the 'width' of the bump can be modified to convey more or less information to the user. The bump can also be used to reduce attention on tasks requiring fine motor control. For example, discrete targets can be located inside two adjacent bumps to prevent the user from slipping off the target. In our implementation, the friction force ramps up rapidly when the outer race reaches a certain position and the friction force increases rapidly to 0.03 Nm resistive torque in 150 ms, and rapidly ramps down after a short distance (e.g., 5°).



USER STUDY

To explore whether passive kinesthetic force feedback can be an effective, recognizable output channel within the context of smart ring use, a user study was conducted. It examined how well participants could perceive and distinguish the force profiles previously described.

Participants

Sixteen paid participants (eight females), between the ages of 22 and 30, participated in the study. All participants were right-handed.

Apparatus and Task Conditions

While walking, the movement of their hands and body may impact one's ability to accurately perceive some force profiles. Thus, to allow for the evaluation of the ring within more ecologically-valid scenarios, a treadmill was used to. Similar to [4], in the *walking* condition, participants had to perform

each experimental task while walking on a motorized treadmill at a speed of 3 km per hour. In the *standing* condition, participants performed the tasks while standing stationary on the treadmill. A 27-inch computer monitor was placed in front of the treadmill, facing each participant, to display the experimental user interface to them (Figure 4).

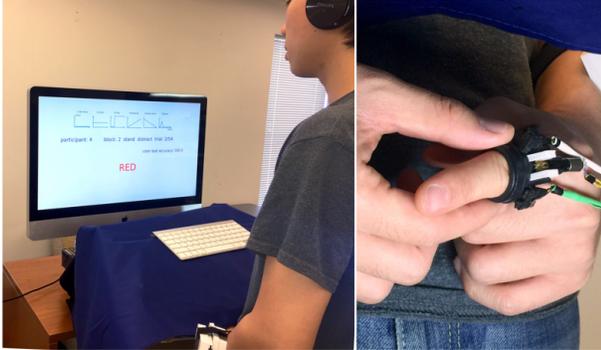


Figure 4. The study setup. Left: A participant is standing on a treadmill. Right: His hand is hidden under the cardboard cover while he rotates the ring to feel the current force profile.

In addition to identifying which profile was being presented, on some trials, participants also performed a secondary task to induce cognitive load. This task was introduced to divert participants' attention from the force pattern identification task, simulating a scenario such as interacting with the ring when talking to a colleague or listening to a presentation. When the secondary task was presented (*Cognitive Load*), participants were asked to perform both tasks in parallel. A modified Stroop test [38] was used, where the name of a color was shown using a random font color (e.g., the word "red" shown using a yellow font color). To ensure the two tasks were performed simultaneously, instead of sequentially, the text and color were randomly rendered from a pool of five colors (e.g., red, yellow, green, black, and blue) every two seconds. Participants were asked to count how many times there was a match between the text and font color. Two seconds was chosen based on results from an earlier pilot study to ensure that participants had enough time to process the task. When the secondary task was not used (*No Load*), participants were not presented with the Stroop task and only indicated which force profile they felt.

In the Resistant Force and Ramp-Down conditions, as the force was expected to be felt immediately after participants attempted to rotate the ring, the brake was engaged immediately after the trial began. Ramp-Up, in contrast, began with no force. Both Ramp-Down and Ramp-Up started at 0° and ended after the outer race was rotated 180°. Hard Stop and Bump were rendered at the 40° position. The position was determined based on data from an earlier pilot study, where a single clutch of the ring would rotate it 40° and still provide a sufficient leading distance so that it would not be confused with No Force. As the brake pad has to move into position at the beginning of each trial, we moved the brake pad a random distance before moving it to the correct

position to avoid the possibility that the vibration of the brake pad would indicate the current force profile.

During the experiment, participants wore noise cancelling headphones to block the noise generated by the ring's motor, yet enable them to listen to the audio feedback from the experimental software. The experimental software was written in Python, and was run on a MacBook Pro laptop.

Procedure

Participants were shown the Frictio prototype and were asked to wear the ring on the index finger of their non-dominant hand. They were then told that they would be presented with one of the force profiles and would need to indicate which force profile it was. After being shown the prototype device and putting it on their finger, each force profile was presented to the participant. Each participant was allowed several practice trials in each condition to familiarize themselves with the force profiles.

During each trial, participants were asked to rotate the outer race using their dominant hand to feel the force profile. Participants were allowed to try a profile as many times as they wanted until they felt confident they could report which one it was. To end the current trial, participants used their dominant hand to press the space bar on the keyboard to finish the trial. They then verbally told the experimenter which force profile was presented. To begin the next trial, participants pressed the space bar again. In the condition, where a secondary task was presented (i.e., the modified Stroop test), participants performed the two tasks in parallel. The percentage of correct responses to the cognitive task was shown on the monitor and participants were asked to maintain an accuracy above 90%. Each participant successfully maintained the 90% accuracy threshold. Breaks were encouraged at the end of each condition.

During the study, participants' hands were covered using a cardboard box to avoid visual cues from the ring potentially influencing their responses. To feel the force profiles, participants were asked to rotate the ring towards their body. Each force profile, except for the Hard Stop could be felt again after the race had been rotated an excess of 180°, at which time a beep indicated the end of the profile. Hard Stop could not be felt again as the outer race was locked at 40°.

Upon completion of the study, participants filled out a post-experiment questionnaire where they indicated subjective ratings for the recognizability of the force profiles (1: *very hard to recognize*, 7: *very easy to recognize*). The experiment lasted approximately 60 minutes.

Experimental Design and Measures

The experiment employed a 2×2×6 within-subject factorial design, with Mobility (*Walking and Standing*), Secondary Task (*Cognitive Load and No Load*), and Force Profile (*Hard Stop (S)*, *Resistant Force (RF)*, *Ramp-Up (RU)*, *Ramp-Down (RD)*, *Bump (B)*, and *No Force (NF)*) as independent variables. The experiment was comprised of three blocks of trials, with each block consisting of 3 repetitions. During

each trial, participants performed tasks in one of the *Mobility* × *Secondary Task* × *Force Profile* combinations. The *Mobility* × *Secondary Task* combination was counter-balanced among participants. The *Force Profile* was presented in a random order. The experimental design was thus 2 *Mobility* × 2 *Secondary Task* × 6 *Force Profile* × 3 *Blocks* × 3 *Repetitions* × 16 *Participants* = 3456 trials.

Dependent measures included the profile recognition accuracy (i.e., the number of correctly identified force profiles), the response time (i.e., the time elapsed from the start of the force profile to the depressing of the space bar), and the number of attempts required to identify each force profile. The response time for *Hard Stop* and *Bump* was measured from the moment when the force was detectable.

Results

The data were analyzed using repeated-measures ANOVA and Bonferroni corrected paired t-tests for pair-wise comparisons.

Profile Recognition Accuracy

The average accuracy across all conditions was 94.0% ($SD = 10.5\%$; Figure 5 right). The repeated measures ANOVA yielded a significant effect of *Mobility* ($F_{1,15} = 17.76, p < .01$), *Secondary Task* ($F_{1,15} = 11.57, p < .01$), and *Force Profile* ($F_{5,75} = 10.3, p < .01$). An interaction was also found between *Mobility* and *Secondary Task* ($F_{1,15} = 5.75, p < .05$), indicating that mobility has a slightly smaller impact when there is cognitive load (Figure 5 left). Recognition accuracy was significantly higher when participants were standing ($M = 95.7\%, SD = 8.8\%$) than walking ($M = 92.2\%, SD = 11.7\%$; $p < .05$) and when no secondary task was present ($M = 95.31\%, SD = 8.54\%$; $p < .05$). *Hard Stop* ($M = 99.5\%, SD = 2.4\%$) was significantly higher than *Resistant Force* ($M = 90.6\%, SD = 13.3\%$), *Ramp-Up* ($M = 91.3\%, SD = 9.8\%$), and *Ramp-Down* ($M = 87.7\%, SD = 14.3\%$; all $p < 0.05$). No significant difference was found between *Hard Stop*, *Bump* ($M = 98.4\%, SD = 3.9\%$), and *No Force* ($M = 96.4\%, SD = 7.2\%$; all $p > 0.05$) or between *Ramp-Down*, *Ramp-Up*, and *Resistant Force* (all $p > 0.05$).

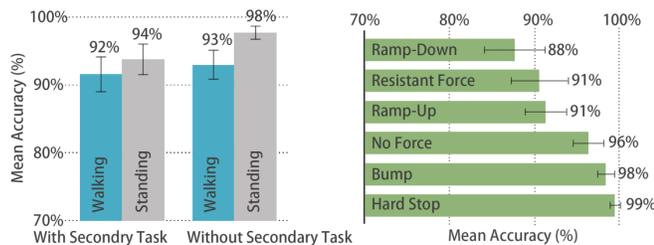


Figure 5. Profile Recognition Accuracy. Left: Secondary Task and Mobility. Right: Force profiles. (Error bars show 95% CI in all figures).

Confusion matrices of the recognition accuracy of different force profiles under the *Mobility* and *Secondary Task* conditions (Figure 6) revealed that the *Resistant Force* was the major source of confusion with *Ramp-Up* and *Ramp-Down* when the task was performed when walking or with the *Secondary Task*.

	Without the Secondary Task						With the Secondary Task						
	No Force	Resistant Force	Hard Stop	Ramp-Up	Ramp-Down	Bump	No Force	Resistant Force	Hard Stop	Ramp-Up	Ramp-Down	Bump	
No Force	97.9	0.7	0.0	1.4	0.7	0.0	95.1	1.4	1.4	1.4	4.9	0.0	Standing
Resistant Force	0.7	98.6	0.7	2.8	2.1	0.0	1.4	88.2	0.0	8.3	4.9	0.0	
Hard Stop	0.0	0.0	99.3	0.0	1.4	0.0	0.0	0.7	98.6	1.4	0.0	1.4	
Ramp-Up	0.0	0.7	0.0	95.8	0.7	0.0	0.0	6.3	0.0	89.6	0.0	0.0	
Ramp-Down	1.4	0.0	0.0	0.0	95.1	0.0	2.1	3.5	0.0	0.0	86.8	0.7	
Bump	0.0	0.0	0.0	0.0	0.0	100.0	0.7	0.0	0.0	0.0	3.5	97.9	
No Force	97.2	2.1	0.0	2.1	4.9	1.4	94.4	1.4	0.7	0.0	7.6	0.0	Walking
Resistant Force	0.0	87.5	0.0	2.8	8.3	0.7	2.1	88.2	0.0	8.3	9.7	0.0	
Hard Stop	0.0	0.0	100.0	2.1	0.0	0.0	0.0	0.0	99.3	2.1	0.0	0.7	
Ramp-Up	0.0	4.9	0.0	92.4	0.0	0.0	0.7	5.6	0.0	88.2	0.0	0.0	
Ramp-Down	2.1	5.6	0.0	0.7	86.8	0.0	2.8	4.9	0.0	0.0	81.3	1.4	
Bump	0.7	0.0	0.0	0.0	0.0	97.9	0.0	0.0	0.0	1.4	1.4	97.9	

Figure 6. The confusion matrices of the Profile Recognition Accuracy (%), by Secondary Task and Mobility.

Response Time

The average response time was 3.1 seconds ($SD = 1.3$ seconds). A repeated-measures ANOVA yielded a significant effect of *Secondary Task* ($F_{1,15} = 13.17, p < .05$) and *Profile* ($F_{5,75} = 83.62, p < .05$). There was no significant effect of *Mobility* ($F_{1,15} = 1.644, p = .219$), nor any significant interaction effects (all $p > 0.05$).

The response time for walking and standing were 3.2 seconds ($SD = 1.3$ seconds) and 3.1 seconds ($SD = 1.4$ seconds) respectively. Surprisingly, response time was faster with the secondary task ($M = 2.8$ seconds, $SD = 1.1$ seconds) than without it ($M = 3.4$ seconds, $SD = 1.5$ seconds). Participants reported that they felt the faster they performed the task, the fewer number of colors they needed to memorize.

As expected, the response time for *Hard Stop* ($M = 1.7$ seconds, $SD = 0.6$ seconds; all $p < 0.05$) was the shortest, followed by *Bump* ($M = 1.9$ seconds, $SD = 0.6$ seconds; all $p < 0.05$). This was to be expected as these two profiles were distinguishable earlier in each trial, after only 40° of rotation. The remaining force profiles required participants to rotate the ring for longer, increasing the response times. No significant difference was found between *No Force* ($M = 3.7$ seconds, $SD = 0.9$ seconds), *Resistant Force* ($M = 4.0$ seconds, $SD = 1.2$ seconds), *Ramp-Up* ($M = 3.9$ seconds, $SD = 1.1$ seconds), and *Ramp-Down* ($M = 3.6$ seconds, $SD = 1.2$ seconds; all $p > .05$; Figure 7 left).

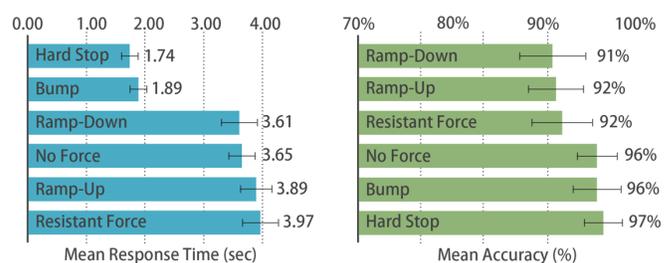


Figure 7. Left: The average response time (in seconds). Right: The secondary task accuracy for each force profile.

Number of Attempts

On average, participants took only 1 attempt ($SD = .09$) to correctly guess each profile. There was no significant effect of

Mobility ($F_{1,15} = .22, p = .644$), Secondary Task ($F_{1,15} = 1.48, p = .24$), or Force Profile ($F_{5,75} = 1.52, p = .23$). Unsurprisingly, Hard Stop resulted in exactly one attempt as the ring was not rotatable once the profile was executed.

Secondary Task Accuracy

The overall accuracy of the Secondary Task was 94.1% ($SD = 8.2\%$). There was a significant effect of Mobility ($F_{1,15} = 11.667, p < .05$) and Profile ($F_{5,75} = 4.413, p < .05$).

Participants completed the secondary task more accurately when standing ($M = 95.7\%, SD = 7.5\%$) than walking ($M = 92.5\%, SD = 8.6\%$). Regarding the effect of Force Profile, the secondary task received higher accuracies with Hard Stop ($M = 96.9\%, SD = 5.8\%$), No Force ($M = 96.2\%, SD = 6.1\%$), and Bump ($M = 96.2\%, SD = 7.3\%$), than Resistant Force ($M = 92.4\%, SD = 9.1\%$), Ramp-Up ($M = 91.7\%, SD = 8.5\%$), and Ramp-Down ($M = 91.3\%, SD = 10.1\%$). Post-hoc comparisons only revealed a significant difference between Hard Stop and Ramp-Down ($p > .05$; Figure 7 right).

Subjective Ratings

Study results were analyzed using Friedman signed-rank tests with Wilcoxon tests for pair-wise comparisons. The Friedman test yielded a significant difference in Force Profile ($\chi^2(5) = 43.74, p < 0.001$). Overall, median ratings for all scenarios were above 5 (with 1 indicating the profile was very hard to recognize and 7 being very easy to recognize). This suggests that all or most of the participants agreed that the force profiles were easy to perceive (Figure 8). Bump and Hard Stop were rated very easy to perceive (i.e., both received a median of 7), followed by No Force. Participants rated these three force profiles significantly easier to perceive than Resistant Force, Ramp Up, and Ramp Down (all $p < 0.005$). Post-hoc tests found no significant difference between the two groups of force profiles (all $p > 0.05$). As the subjective ratings are consistent with the recognition accuracy results, this confirms the effectiveness of passive kinesthetic force feedback as a new output channel.

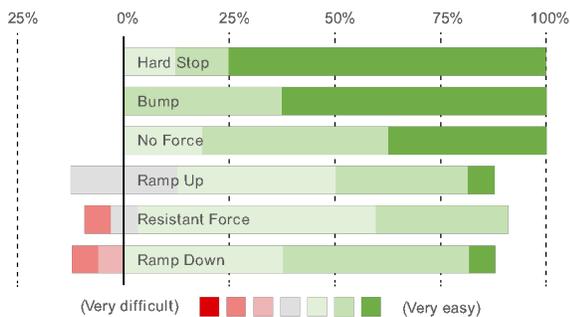


Figure 8. Participant responses to the ease of recognizability of the force profiles. Graphs are centered around the neutral response, with the proportion of positive and negative responses on the right and left side, respectively.

Participants were welcoming of this new output technique as well. They described it as “interesting” (P2, P8, P9), “awesome” (P6), “cool” (P15), “promising”, (P16), “exciting” (P11), and “amazing” (P3). They told us that

they could imagine new applications that could be enabled by this type of haptic feedback (e.g., “I am looking forward to seeing new applications” (P14)). Participants also saw potential for such a ring in scenarios such as “sports & yoga” (P7) or during “fitness” (P10). Two participants also noted the intimate nature of the ring, suggesting it could be used “between lovers” (P14) or for “private communication” (P10).

Discussion

The user study indicated that most force profiles could be easily distinguished, even under conditions where users’ physical or mental workload was high. Walking or performing a secondary task had a negative impact on participant’s ability to accurately perceive the haptic feedback. It is important to note is Resistant Force was a major source of confusion because of its similarity to Ramp-Up and Ramp-Down. Although distinguishing between the three was not difficult when full attention was paid, accuracy decreased when participants had to walk or their attention was divided between two tasks. For designers of haptic interactions, if Ramp-Up/Down has to be included in the vocabulary, patterns similar to Resistant Force should be avoided to reduce potential confusion.

A promising finding was that physical or mental workload did not significantly impact response time. Surprisingly, response time was even shorter when participants were asked to perform a secondary task, requiring extra cognitive load. Furthermore, faster responses did not diminish participants’ ability to correctly identify the force profiles. Decreases in response time are likely due to participants wanting to complete the trial as quickly as possible to reduce the number of memorizations required in the secondary task. More research is needed to determine how these results transfer to other scenarios. Across all conditions, including physical and mental workload, Hard Stop and Bump were easily perceived, making them excellent candidates for conveying critical signals. Response times for Hard Stop and Bump were also quite quick. In contrast, Ramp-Up and Ramp-Down took participants significantly longer to distinguish, as users needed to rotate the ring far enough to feel the change in the force magnitude. Response times may decrease if the slope of the force profile increases.

The unique properties of the different force profiles allow them to be suitable for different applications. For example, Hard Stop and Bump seem more appropriate to indicate urgent messages, as they can be recognized quickly. Ramp-Up and Ramp-Down seem most suitable if one wants to mimic physical feedback during physical interactions. Therefore, the value of the force profiles value may lie in the realistic feelings that could be provided to users in applications where haptic feedback is important (e.g., games), or in designing novel metaphors for the ring (e.g., closing an application is accompanied by the Ramp Up to mimic the closing of the lid on a soda bottle).

The study also demonstrated how clear each force profile was via the number of attempts that were required to complete a trial. In situations where two or more force profiles were

indistinguishable by participants, e.g., Ramp-Up and Resistant Force, the participant may have spent more time on decision making than physically rotating the ring multiple times to get a clear feeling. In either case, response time may have been longer, but less attempts would have been made, i.e., the classic speed-accuracy tradeoff. As the average number of attempts made was close to one, the participants could readily feel the haptic feedback patterns. Similarly, decision making did not take extra time away from participants while identifying the right force profile. This confirms that passive kinesthetic haptic feedback does not divide attention to the degree that it imposes a significant cognitive load on users.

Smart rings are expected to be used on-the-go, while users are performing another task and have their attention divided. It was thus important to understand if interacting with the ring through the passive kinesthetic haptic feedback would impact the performance of the user's task. Our results demonstrated that the average accuracy of the secondary task was around 94%. This suggests that ring-based passive kinesthetic haptic feedback may not significantly impact the performance of a second, parallel task. On the other hand, physical workload did have an impact on haptic perception: the accuracy was higher when standing than walking. These results were like caused by the movement of the user's hands and body, but still indicate that passive haptic feedback could be useful for multi-tasking. If a passive kinesthetic haptic feedback-enabled ring is to be used in a context-aware application that detects physically activity, one may want to alter the force patterns that are supported so as to improve recognition rates.

EXAMPLE SCENARIOS

To demonstrate potential usage scenarios for ring-based, passive kinesthetic haptic feedback, and explore the range of tasks that it may be best suitable for, we implemented four applications. The applications exemplify novel interactions techniques that could enhance common, everyday tasks.

Calendar

It is common that individuals check the time on their smartphone or smartwatch to plan for the next appointment in their calendar. Frequently looking at your watch, however, is considered inappropriate in many social settings. With Frictio, the amount of friction force and rotation allowed can be used to indicate the time remaining until one's next meeting. For instance, if there is over an hour until the next meeting, the ring can freely rotate for a full rotation (Figure 9), but if there are only 15 minutes, the ring can be made to feel stiff, and would stop rotating after a 90-degree rotation. If one was late to a meeting, the ring could become unmovable. Such an application would employ three of the patterns tested in the prior study (No Force, Resistant Force, and Hard Stop) and could utilize greater gradations of resistant force to provide more expressivity.

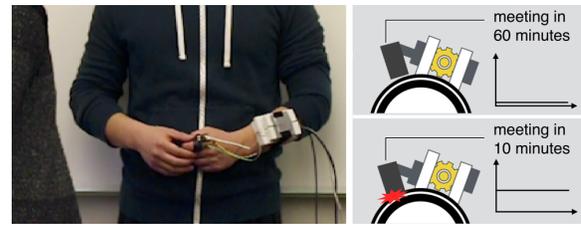


Figure 9. With Frictio, a user can subtly check their calendar while chatting.

Rotary Combination Lock

Providing precise rotary input on a smart ring can be challenging, as pointing at a small angular target requires fine motor control or continuous visual attention [2]. This challenge can be mitigated by providing haptic landmarks around the targets using the Bump force profile. To demonstrate this capability, we implemented a rotary combination lock to allow a wearer to unlock their personal computing devices (e.g., smartphone or laptop) using the ring (Figure 10 left). Passwords can be entered as a series of three rotations that alternate direction, followed by a fourth direction change to confirm the inputted sequence. The device provides Bump feedback every 45° of rotation. Eyes-free input is also possible as the user can memorize how many times the dial needs to be turned across the haptic landmarks in a certain direction. If the correct sequence of rotations is entered, the ring will spin freely (No Force) to indicate success. A Hard Stop would be used to indicate a failed attempt.

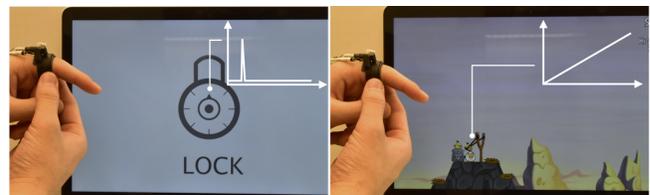


Figure 10. With Frictio, (Left) a wearer can unlock their laptop by using their ring as a combination lock, or (Right) control the angle and power of a slingshot while gaming.

Gaming

Inspired by the popular Angry Birds mobile game, Frictio can also be used for traditional gaming input, by mapping the rotational nature of the device to input. Using Frictio, the wearer can rotate the outer race to indicate the angle of the birds' slingshot. After a one-second dwell, the mode is switched to input the power of the slingshot. During pull-back, the Ramp-Up profile informs the wearer that the slingshot is approaching the maximum force (Figure 10 right). The wearer can then quickly rotate the ring in the opposite direction, which switches to No Force, and gives the wearer the sensation of a large spring force being released as the motor disengages the brake. This example showcases the novel haptic output responses that can be generated in response to user input to provide a richer gaming experience.

Eyes-Free Call-Display

If the wearer is at a movie theatre with their phone on silent and they receive a phone call, they may want to know who is calling before deciding whether to leave and answer the call. If they take the phone from their pocket to see the screen, the glow it emits will disrupt the other viewers. Instead, when the phone vibrates, the wearer can twist Frictio to query the caller. As the wearer has memorized predefined mappings for frequent callers, they know that if they twist the ring and feel the No Force profile, it is an unknown caller, whereas if they feel the Hard Stop profile, it is their wife calling and they should answer the call (Figure 11).

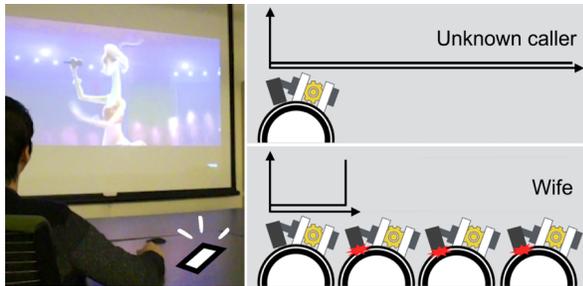


Figure 11. With Frictio, a user can check who is calling by associating different force profiles to different incoming callers.

FUTURE WORK

The implementation, evaluation, and applications that were developed for Frictio demonstrated the viability and potential of ring-based, passive kinesthetic haptic feedback, however, there are many lines of research that are ripe for exploration and innovation.

Miniaturization and compactness are important aspects of any wearable [1], especially those found on the finger. The current implementation of the ring was sufficient to evaluate the six force profiles, however, it could be iterated on to further reduce the physical footprint on one's finger. For example, one could replace the gear motor with a smaller actuation mechanism such as an ultrasonic motor, or better integrate the Hall Effect and proximity sensors within the body of the ring. In addition, as the brake pad is made of rubber it will eventually wear away and require replacement. Developing a quick-change mechanism or using a stronger durometer of rubber, will increase the longevity of the braking system. Lastly, the current prototype was designed to fit on a finger whose ring size was 8. As the ring needs to be worn tightly on the finger, we padded the inner race for participants with thinner fingers to achieve a firm friction fit. Future work will develop the ring in different sizes and test the usability of it in real-world situations.

Being at an early stage of this research and development, the presented study focuses on simple force profiles to demonstrate the promise of the Frictio concept. Future research is needed to explore more complex cases. Additionally, the present evaluation focused on the *discriminability* of each of the haptic force profiles. While

the results indicated that some profiles were easier to distinguish, and would be better suited for some applications than others (e.g., Bump and Hard Stop), the current experiment was unable to determine the *perceivability* of such passive, kinesthetic haptic feedback. Just noticeable difference experiments could be conducted to understand the minimal amount, and varying levels, of passive feedback that a wearer is able to detect. The outcomes of such studies would not only uncover the limits of finger-based human perception, but also afford developers opportunities to map force levels to specific notification types, or indicate event immediacy or location proximity. Understanding wearers' abilities to perceive the frequency of alternative haptic patterns such as bumps, detents, notches, or axial movements along the ring's outer race would also be a fruitful line of experimentation to undertake.

Currently, Frictio is operated by wearing the ring on one's non-dominant hand, and interacting with it using two fingers on their dominant hand. While this mimics natural fidgeting behaviors, there are many instances where the dominant hand may be busy [14]. The present experiment and applications did not explore the one-handed use of such a smart ring, for example, worn on the middle finger and engaged with the thumb. As one-handed use could change the region of the finger that is providing input and receiving output from the ring (i.e., fingertip versus finger pad), it will be important to understand the implications of this on distinguishability and perceivability. Further, as attention is likely even more divided when the non-dominant hand is occupied (e.g., carrying a bag, holding onto a support strap on a bus), it remains to be seen the influence that activities with extreme cognitive load would have on the ability to recognize and utilize passive kinesthetic haptic feedback.

CONCLUSION

In this paper, we propose the use of passive kinesthetic force feedback for rotational input on smart rings. With such feedback, different friction forces can be designed, generated, and felt by a user when they rotate the ring. We designed six force profiles and developed a proof-of-concept prototype, *Frictio*, to demonstrate the potential of this new type of force feedback on a smart ring. Through a controlled experiment, we determined the recognizability of the six force profiles within the context of smart ring use, including walking and standing, and with and without a secondary task. The results demonstrated that participants could distinguish between force profiles with 94% accuracy with an average response time of 3.1 seconds. Initial user feedback suggested that participants welcomed the passive kinesthetic haptic feedback and thought of it as a useful addition to smart rings. Through a set of novel interaction techniques, we demonstrate the unique capabilities enabled by this novel haptic output channel. This work thus provided new insights into richer output methods on smart rings and other finger-worn wearable devices.

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