RollingStone: Using Single Slip Taxel for Enhancing Active Finger Exploration with a Virtual Reality Controller

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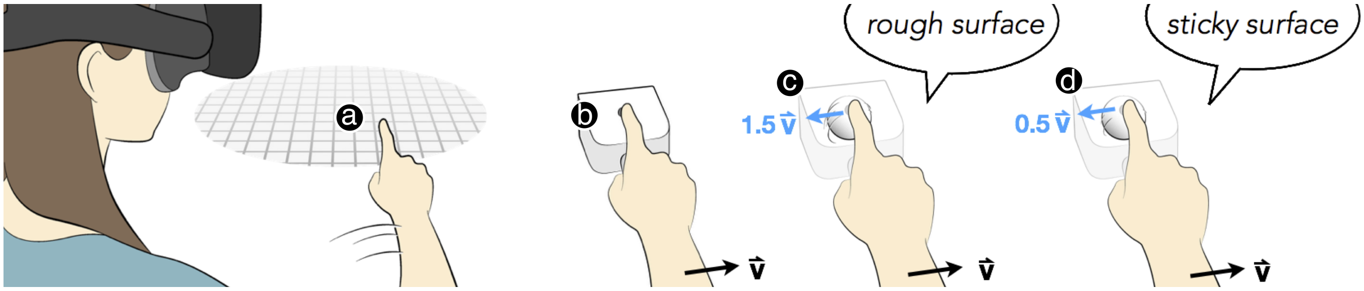

Figure 1. RollingStone aims to enhance the experience of textures when users engage in active finger exploration in virtual reality. When the user (a) engages in active finger exploration on a virtual surface, (b) the 2-degree-of-freedom ball-based slip display generates various perceptions of texture by applying (c) faster or (d) slower relative slip speeds between the finger and the actuated ball.

ABSTRACT

We propose using a *single* slip tactile pixel on virtual reality controllers to produce sensations of finger sliding and textures. When a user moves the controller on a virtual surface, we add a slip opposite to the movement, creating the illusion of a finger that is sliding on the surface, while varying the slip feedback changes in lateral forces on the fingertip. When coupled with hand motion the lateral forces can be used to create perceptions of artificial textures. RollingStone has been implemented as a prototype VR controller consisting of a ball-based slip display positioned under the user's fingertip. Within the slip display, a pair of motors actuates the ball, which is capable of generating both short- and long-term two-degree-of-freedom slip feedback. An exploratory study was conducted to ensure that changing the relative motion between the finger and the ball could alter the perceptions conveying the properties of a texture. The following two perception-based studies examined the minimum changes in speed of slip and angle of slip that are detectable by users. The results help us to design haptic patterns as well as our prototype applications. Finally, our preliminary user evaluation indicates that participants welcomed RollingStone as a useful addition to the range of VR controllers.

Author Keywords

Haptics; Controller Design; Tactile Display; Slip Display; Virtual Reality.

INTRODUCTION

For many of today's virtual reality (VR) systems, a handheld controller is a popular interface for users to interact with the virtual world. Since VR controllers are highly mobile and need not be worn, they support large workspaces but require little in regard to effort at configuration. However, owing to the limited output options of VR controllers and the need for body-grounded implementation, the potential of controller-enabled haptics remains not fully exploited to date.

In this paper, we investigate utilizing a single slip tactile pixel (or *slip taxel*) to enhance the experience of active finger exploration with VR controllers. When a user moves a controller on a virtual surface, the controller displays a backward slip feedback accordingly, as if the user's finger is sliding on the surface. When coupled with the finger motion, the perception of textures can be produced by varying the speed of slip changes via lateral forces on the fingertip. Our solution is based on two exciting observations from previous works in which researchers found (a) changing the relative speed between finger and slip surface alters the perception of roughness [4], and (b) rich texture experiences can be created on a flat surface by changing the lateral forces applied on a sliding

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finger [40]. We thus implemented a prototype controller consisting of a ball-based slip display. As illustrated in Figure 1, the ball is positioned below the user's index fingertip. The slip display actuates a ball by utilizing a pair of motors capable of producing a two-degree-of-freedom slip.

Different from existing controller-enabled haptic feedback such as vibrations, weight shifting [60], grasp resistance [7], or normal force [2], we focus on supplementary slip sensations and lateral-force-based texture experiences. Recently, Whitmire, *et al.* [55] proposed using an actuate wheel on a VR controller to generate slip feedback from which users can feel surface textures via the physical haptic features augmented on the wheel. By customizing such wheels, versatile perceptions of texture are also possible. Instead of utilizing configurable wheels and physical textures, our approach generates programmable experiences of texture via a single slip taxel, which can help future designers create texture experiences with limited numbers of physical haptic elements.

To explore the capabilities of our approach, we designed and implemented a RollingStone prototype using it to devise one explorative study and two psychophysical studies. In the explorative study, we collected users' subjective feedback by asking them to feel six slip profiles and report their experiences. The results suggest that by varying the parameters of slip, participants could experience both their finger sliding and the changes indicating different properties of texture. In the second and third studies, we examined the Just Noticeable Difference (JND) Values of the two factors of slip, the slip speed and the slip angle relative to hand motions. We applied an adaptive staircase procedure to find the noticeable changes of relative speeds ranging from 7.89mm/s to 21.77m/s for different hand motions. The results show that, with increasing speed of hand exploration, the system needs to increase the magnitude of slip speed to change the sensations of texture. Then, we investigated how precisely the angle between slip and hand motion needs to be matched. The results show that the slip direction does not need to be perfectly aligned with a given hand motion. The resulting discrimination thresholds of the relative angle are at least 49.50°. These results provide insights for future designers creating slip profiles as well as applications. Finally, to demonstrate our interaction techniques, we developed three VR applications tailored for RollingStone. These applications were used in a preliminary user evaluation to gain understanding of controller-enabled slip feedback.

The primary contributions of this study are: (1) the notion of slip feedback on virtual reality controllers; (2) the results of three user studies that investigate the capabilities of slip; (3) the implementation of RollingStone, a proof-of-concept prototype; (4) a set of usage applications to demonstrate RollingStone's capabilities; and (5) the results of a preliminary user evaluation.

RELATED WORK

Grounded haptic devices, such as PHANToM [27] or Falcon [51], are actuated mechanical structures with fixed bases in the environment. Although they can generate strong and rich external forces, these types of devices are stationary and bulky, which limits the user's workspace. Considering the need of higher portability and mobility, researchers have proposed various forms of wearable and handheld haptic devices, where the grounding is moved from the environment to the human body, which is regarded as body-grounded implementation. We review the related literature on body-grounded haptic devices for virtual reality, slip feedback and slip displays, and techniques for rendering programmable textures. Comprehensive reviews can be found at [11, 33, 9].

Body-Grounded Haptic Devices for Virtual Reality

Wearable haptic devices have drawn much attention due to their capability of rendering rich haptic feedback. For kinesthetic feedback, researchers have developed exoskeleton gloves, where the simulated forces are provided by actuated linkages between fingers and an on-body ground. The grounded points include the wrist [14, 15], palm [3], back of the hand [23], and thumb [6]. Researchers have also proposed fingertip-worn devices generating cutaneous feedback, where they have utilized skin deformations by actuating a plate or a tactor in contact with the fingertip. The normal or lateral skin deformations are used to simulate different types of tactile interactions, such as pressure [58], curvature [37], hardness [35], and friction [47].

If compared to wearable haptic devices, handheld devices are more compact and need not be worn, allowing users to engage in quick VR interactions. However, the capabilities of recent commercial VR controllers mainly provide vibrotactile feedback. More output modalities remain to be exploited. Previous works have explored creating haptic feedback on grasping [16] or mass location [60]. Benko *et al.* proposed NormalTouch and TextureTouch [2]. The tilt and shape displays on controllers create contact force and surface-like textures. RollingStone differs from tilt and shape displays that produce haptic feedback by skin indentations; it investigates slip during active finger exploration. Haptic Revolver is a reconfigurable VR controller that also enables active exploration by placing multiple haptic features on a 1-DoF rotational wheel [55]. Instead of using physical haptic textures, designers are not limited by the physical textures available and can easily produce various slip profiles for reuse in VR applications when using our device. In addition, users do not need to replace a taxel before changing VR applications. Since each haptic feature occupies limited wheel space and only rotates in 1D, the authors proposed generating nonstop wheel reversals and horizontal rotations to simulate long-distance 2-DoF finger sliding. Different from their strategies, RollingStone utilizes single 2-DoF slip display to generate the illusion of finger sliding and lateral-force-based experiences of texture. To reach our goal, two JND studies were conducted to examine users' sensory limits in relation to slip speed and slip angle during active finger exploration.

Studies on Skin Stretch and Slip Feedback

Skin Stretch. In many VR applications, skin stretch is often used for creating incidental tactile feedback. For example, Hayward *et al.* implement an array of piezoelectric actuators that reproduce lateral skin stretches on fingertips [17]. Minamizawa *et al.* propose using finger-worn belts for skin stretches when grabbing a virtual object. Others utilize actuated tactors under the user's fingertip to generate the skin stretch when grasping or lifting an object [45], or creating the surface friction with an actuated tactor mounted on a PHANToM device [38]. Recently, researchers found asymmetric vibrations are able to create skin pulling sensations with directional cues [39, 10]. Culberson *et al.* hypothesize that it is because asymmetric vibrations result in asymmetric lateral skin deformations [9]. Also, Grabity utilizes asymmetric vibration to simulate weight when lifting a virtual object [5]. However, sensations created by these devices are from short-range skin displacement, which are more suitable for directional notification or manipulation tasks.

Slip Feedback. Slip is caused by the relative motion between the fingertip and the surface. Although human slip perception remains underexplored [20], researchers have found that the perception provides tactile cues of the relative speed and the relative orientation [43]. Such cues are important during dexterous object manipulation [22] as well as recognizing surface textures [42]. Early works also found that a rotating drum mounted on the desktop could recreate a perceptually convincing slip and skin stretch tactile effects [41, 44].

To generate slip feedback, researchers proposed a ball-based slip display that can generate continuous slip sensations. TouchBall [8] is a handheld 2-DoF slip display. The device contains a ball actuated by two motors that provides directional cues to users. Webster *et al.* proposed a 2-DoF rolling ball device integrated with a PHANToM device. The device was used for simulating the slip sensation while dragging objects in VR [54]. Slip Aestheasis [52] uses a pair of V-shaped motors mounted upon user's fingertip. The authors evaluate how well users can differentiate slip directions from their prototype system. Ho *et al.* propose generating both lateral and rotational slip by interleaved tactile belts [18]. Despite fruitful research findings on slip displays, previous studies mainly focus on receiving slip via a static hand position, and the applications usually target directional cues. In regard to body-grounded implementation, using slip to simulate finger sliding and surface texture remains to be explored. This study aims to integrate a ball-based slip display with a controller, and use it for enhancing active exploration in VR.

Rendering Artificial Texture

Various approaches have been explored for rendering perceptions of artificial textures. Shape-changing displays utilize a matrix of pins to render shape or texture of virtual objects. Piezoelectric or shape-memory-alloy (SMA) pin arrays have been proposed to render perception of fine-grained textures on fingertips by creating both normal [50, 53] or lateral [34] shape changes. On the scale of desktop and tabletop, shape displays have been utilized to add haptic information to visual information [21, 36], or render dynamic affordances for manipulating virtual objects [12], engaging in tele-presence collaboration [26], or enhancing the experience of virtual reality [46].

On touchscreens, T-Pad [56] utilizes ultrasonic frequency, low amplitude vibrations between two flat plates that can create a squeeze film of air between the surfaces of the two plates thereby reducing the friction. Later works further augment a plate laterally to move under the finger, adding both friction and lateral forces to the finger's stimulation [28]. TeslaTouch [1] and its subsequent work [25] apply electrostatic forces. The normal force between the finger and surface is affected by the attraction of electrostatic forces, changing the surface frictions. While these implementations allow active finger exploration, the interaction area is limited by the surfaces.

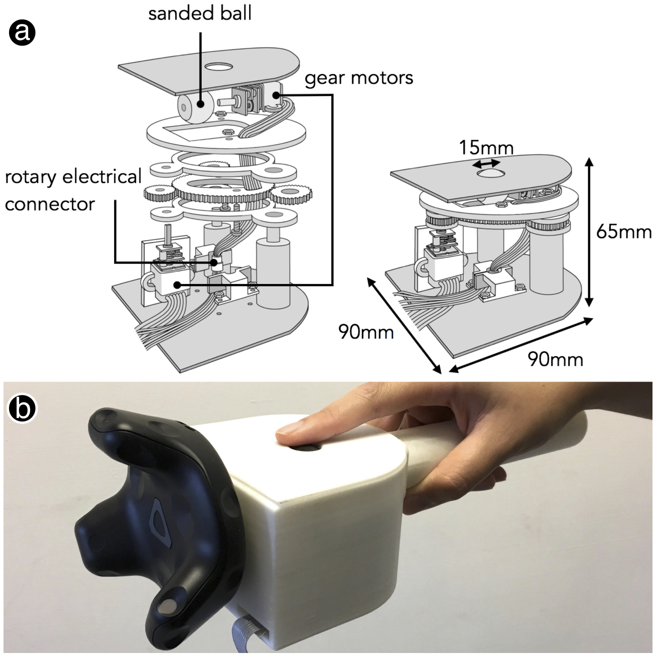

Figure 2. The (a) 3D models and (b) the hardware prototype of RollingStone.

Vibration is also a common means to display artificial textures. As shown in many applications, vibrotactile feedback is often used for recreating the experience of surface textures [29, 24, 48]. Recently, Strohmeier *et al.* also suggested that while holding a probe, coupling user action with vibrotactile feedback can induce rich haptic sensations [49]. Although, it is excluded from this work, vibrotactile feedback could still be added for further enhancements in the future.

ROLLINGSTONE IMPLEMENTATION

We adopt ball-based slip display for our purposes. As illustrated in Figure 2, the ball-based slip display was integrated with an HTC Vive tracker and a handle. The ball was 3D printed with a diameter of 25.4 mm and evenly sanded using 80 grit sandpaper. The diameter was chosen as a reasonable size for the index fingertip. After the polishing, the ball produces smooth slip feedback at different rotational speeds. The slip display is designed with two layers, in which one gear motor is placed in each layer. The metal gear motors are used for actuating the ball, enabling the ball to rotate along the vertical and planar directions. The RollingStone prototype communicates with a desktop computer via a serial connection at 115200 baud.

A Pololu 12V HPCB gear motor with gearheads 298:1 is used at the top layer, and can run at a top speed of 100 RPM. This low-speed motor is connected with the ball and enables the ball to produce slip speeds from 5mm to 130mm/s. A 12 CPR magnetic encoder mounted on the back shaft is used to

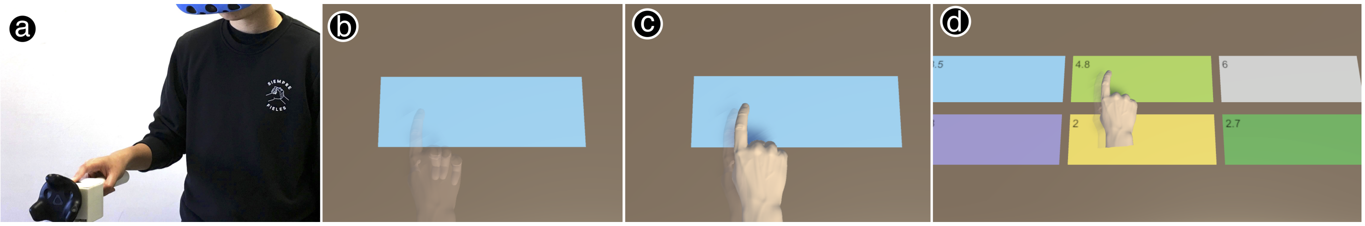

Figure 3. The study environment in STUDY1. (a) The participant holds RollingStone device and aligns it to (b) a semi-transparent hand to (c) experience the slip profile. In each adjustment session of the texture properties, the participant can (d) experience all slip profiles at once.

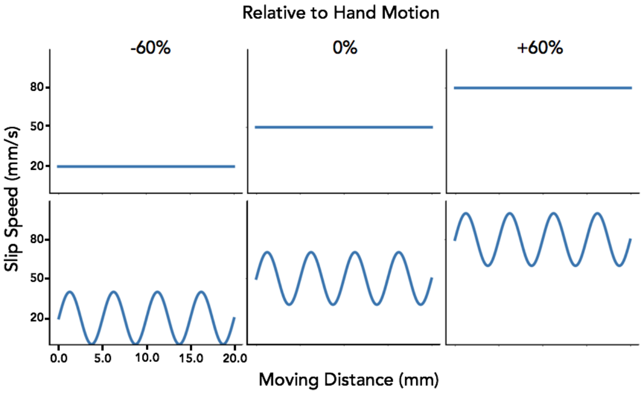

Figure 4. The six slip profiles used in STUDY1.

measure the speed of the motor. A PID loop is implemented for controlling the motor. The PID loop maintains the speed, preventing the motor from being interfered with by the finger. The resolution of the slip speed is 2mm/s, computed from the PID loop and the encoder values. The torque of the low-speed motor is 70oz-inch. With the 25.4mm diameter ball, a thirty-eight Newton normal force is needed to stop the ball, which is enough to resist the force applied by the human finger during slip. As displayed in Figure 2a, to avoid the intertwined wires during the planar rotation, we adopt an epicyclical gearing design with a rotary electrical connector. The gear motor in the second layer (gearheads 30:1) runs with a top speed of 1000 RPM, enabling a 360° rotation within 60 milliseconds. This motor is also controlled by a magnetic encoder and a PID loop. The resolution of the planar rotation is 5°. Finally, a $90 \times 90 \times 65$mm ($l \times w \times h$) case with a 150mm-long, 3D printed handle is used. A 15mm diameter aperture is hollowed out on the case top to allow the finger to be placed on the ball. The edge of the hole offers sufficient support, preventing the finger from slipping off. The hollow is arc-shaped and fits the ball, which makes the edge feel smooth. A VIVE tracker is mounted in front of the case. The device's weight is 260g in total, which is lightweight for long-time usage.

This design is different from previous slip displays, in which two motor-driven wheels actuate the ball via contact friction forces [54, 8]. According to their methods used, the wheels can be arranged orthogonally in a single layer and the slip direction can be interpolated by the two wheel rotations. However, previous works indicate that the wheel-based design would likely encounter slippage errors between the wheels and the ball owing to "kinematic creep" [54]. Undesired tactile feedback may occur when the speed of the slip often changes. Other methods from previous works utilize a permanent magnet as the drive roller[32]. As for these methods, heavy finger pressing could interfere with the friction forces and even stop the ball [8]. To ensure that experiences of finger sliding and textures are consistent, we finally adopted the two-layer design with high-torque gear motors, and use it as an apparatus in the following studies.

STUDY OVERVIEW

During active finger explorations, one perceives both tactile sensations from fingers and the kinesthetic sensations from hand motions, resulting in various texture experiences [49]. In regard to VR controllers, several factors can be associated with haptic sensation, including the weight of the controller, the material of the actuated ball, or how heavily the user's finger presses upon the ball. Given the early nature of this research, we conducted three studies seeking to answer the following questions: (a) Does adding a slip enhance the sensation of sliding? During exploration, what perception of textures do participants experience as a consequence of different slips? Also, when coupled with hand motions, how well can participants discriminate (b) slip speeds and (c) slip angles between the finger and the slip display? The first study helps us to understand if a slip is a valuable addition for active finger exploration in VR. The second and the third studies lead us to understand better participants' sensory limitations and can help us design slip patterns as well as a prototype system.

STUDY1: EXPLORATIVE STUDY

Design

To explore the capabilities of this new controller output, six slip profiles were designed and implemented, as illustrated in Figure 3. These profiles were generated giving weight to two considerations, *Relative Slip Speed* and *Speed Variation*, both of which have been found effective in conveying perception of texture via friction [4] and grooves and ridges on a surface [40]. In a VR environment, participants were asked to use the apparatus and experience the profiles, and to report their experiences and subjective scores on the properties of the textures perceived.

Three properties of texture often evaluated by previous studies were considered, including *Roughness*, *Bumpiness*, and *Adhesiveness* [57, 31]. We excluded additional texture dimensions such as sharpness [49] or softness [31] since a three-participant pilot study suggests that these profiles were not relevant. The pilot study also suggests that when holding the apparatus, typical exploration speeds (*i.e.*, hand motions) ranged between

50mm to 70mm per second. The range of exploration speed is somewhat restricted compared to previous studies on active finger exploration [19], since the experimenter found unsteady hand trajectory easily occurred when exploration speeds were too slow or too fast. In this explorative study, we limited the exploration speed to 50mm/s to reduce the effects of unstable movements.

As shown in Figure 4, three relative slip speeds were chosen, 60% slower (*i.e.*, -30mm/s), 60% faster (*i.e.*, +30mm/s), and equal to the exploratory speed, resulting in 20mm/s, 50mm/s, and 80mm/s slip speeds. The speed variations followed the hand movements, simulating the change of lateral forces caused from the finger sliding on a surface. For the waveform of variation, we chose 0 peak/mm and 0.2 peak/mm, representing the constant lateral force and the periodical changes of the lateral forces. The amplitude of the waveform was set to 40% of the exploratory speed (*i.e.*, 20 mm/s) to make sure participants could clearly sense the variations. The output speed is calculated by:

$$SlipSpeed = v_h \times (1 + v_r) + A \times sin(\int_0^t 2\pi v_h k_v t \mathrm{d}t)$$

Where v_h and v_r represent hand exploratory speed and relative slip speed(%) respectively. A is the amplitude of the waveform, which is 20mm/s here. k_v represents the waveform of variation.

Procedure and Task

The procedures of this study can be categorized over four sessions. Initially, in the preparatory session, this researcher explained the three properties for the selected textures, *Roughness*, *Bumpiness*, and *Adhesiveness*, to the participants, until they reached an agreement on the definition of the three properties. The descriptions of the textures' properties used in this study follow similar definitions in [49]. Participants were then asked to wear a VR headset and grasp our prototype device with their dominant index finger placed on the ball, and then they began the training session.

The goal of the training session was to let participants become familiar with our device and study its interface. As illustrated in Figure 3b, in the VR environment, the participants can first see a rectangular sheet on a table, and a semi-transparent hand above the left edge of the sheet. To start feeling the profile, the participants were instructed to align the controller to the hand. Once the alignment was ready, the hand started to move from left to right with a controlled exploration speed of 50mm/s, and each participant was asked to follow the hand with their controller and to experience the profile, as displayed in Figure 3c. The training session ends when the participant can steadily follow the hand with their controller.

In the formal testing session, the participants were given six profiles to perceive in a random order. For each profile, a sheet appeared on the table in a different color. The difference in color was determined to help participants to discriminate between the profiles. After each participant finished experiencing the profile, the researcher asked the participant to rate the level of realism of the sensation of their finger sliding on a surface. Also, each participant was asked to describe their perception of the texture of each sheet provided in their own words. After their description, 12 nouns related to the textures were presented, and the participants were told to select the nouns that are most closely related to the textures they described. The 12 nouns were adapted from TeslaTouch[1] and our brainstorming results, which include paper, rubber, leather, silk, concrete, wall paint, wood, linen, jeans, skin, sandpaper, and stone. An informal lab study indicates that the nouns are common in daily life. Finally, the participants rated their agreement with scores in regard to the properties of the three textures. Ratings were made based on using a continuous numeric scale, from 1 to 7, with 1 standing for not rough at all and 7 for very rough. Decimal ratings such as 5.7 were permitted. After all the profiles were experienced, the adjustment session began.

In the adjustment session, the participants could adjust their agreement scores with the properties of the textures. As displayed in Figure 3d, for each property of a texture, the participants were shown six sheets at a time. The agreement scores were shown adjacent to each sheet. The participants could then compare the sheets and adjust their scores accordingly, until they were satisfied with the agreement scores.

Participants

Twelve participants (6 females and 6 males) between the ages of 20 and 25 took part in this study. Six of them had had experience using VR headsets and controllers. All of them were right-handed with a normal sense of touch. DTuring the entire study, the participants wore noise canceling headphones to block the motor noise while in a standing position. The sessions took fifty minutes on average.

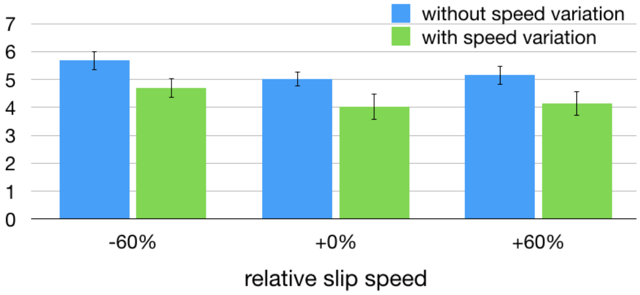

Figure 5. The agreement scores of realism of sliding on a surface. Error bars show standard error in all figures.

Result

The agreement scores for realism in finger sliding are displayed in Figure 5. In general, the participants agree that the slip feedback is consistent with their daily experiences. We conducted a 2-way repeated measure ANOVA on the agreement scores with *Relative Slip Speed* and *Speed Variations* as the independent variables. The results indicate no significant effect in regard to *Relative Slip Speed* ($F_{1.106,12.169} = .4$, $p = .559$), and no significant interaction between the two independent variables ($F_{1.590,17.492} = .101$, $p = 0.862$). However, the results show a significant effect in regard to *Speed Variations* ($F_{1,11} = 6.715$, $p < .05$). The pairwise comparison shows that the speed variations lower the perception of the quality of realism ($p < 0.05$). Some participants report that they "*had not encountered such periodically-changing textures in the real world [P7, P10].*" The results suggest that designers should be especially careful when applying speed variations to their profiles.

The agreement scores of the texture properties are displayed in Figure 6. We conducted 2-way repeated measure ANOVA analyses on the perception of the properties of *Roughness*, *Adhesiveness*, and *Bumpiness*, respectively. The independent variables were *Relative Slip Speed* and *Speed Variation*. The results first indicate for each texture property that the interactions between the independent variables in relation to the textures' properties are not significant (all $p > 0.05$). This is interesting; the results indicate that both relative speed and speed variation can affect the textures' properties, respectively.

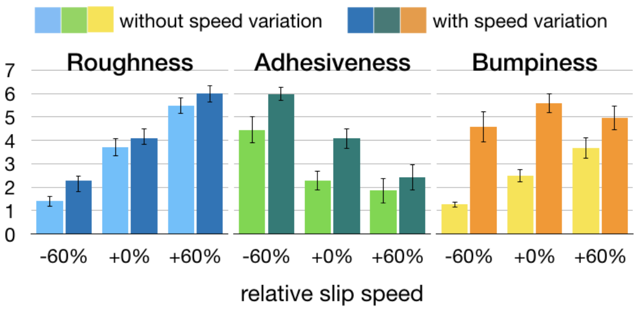

Figure 6. Agreement scores of the texture properties, including *Roughness*, *Adhesiveness*, and *Bumpiness*.

For *Roughness*, the ANOVA results show significant effects of both *Relative Slip Speed* and *Speed Variations* ($F_{1.692,18.615} = 59.555$, $p < .001$; $F_{1,11} = 5.587$, $p < .05$). The pairwise comparisons show that increasing the relative speed or adding the speed variation increases the sensation of roughness (all $p < .05$). Participants were more likened to "silk" and "paper" at lower speeds, and preferred "wood" and "stone" at higher speeds. For the relative slip speeds, the reason could be that faster slip speeds generate stronger tactile stimuli, making the participants state that they "*felt more frictional forces during hand movements [P5, P7, P8].*" For the speed variations, participants report that they perceived "*significant resistance from the virtual surface [P1, P5],*" making them feel that the roughness was increased.

For *Adhesiveness*, increasing relative speed resulted in a decrease in the perception of adhesiveness ($F_{1.463,16.097} = 80.251$, $p < .001$; all $p < .05$ in pairwise comparisons), and adding speed variations significantly increased the perception of adhesiveness ($F_{1,11} = 6.729$, $p < .05$; $p < .05$ in the pairwise comparison). Participants report perceiving a sensation of sliding on "rubber" at lower speed, and referred to median speed as "less adhesive rubber" or "leather", since they felt that "*the virtual surface dragged on the index finger [P2, P8].*" As for the speed variations, similar to *Roughness*, participants report that the changing lateral forces caused a sensation that the virtual surface was sticky and that their fingers were "dragged" on the surface.

Finally, the results show *Bumpiness* scores were significantly affected by both *Relative Slip Speed* ($F_{1.848,20.328} = 5.880$, $p < .05$) and *Speed Variations* ($F_{1,11} = 55.546$, $p < .001$). The pairwise comparisons showed that for the sensations of bumpiness of faster relative speed was significantly higher than the slower relative speed ($p < .05$), and adding speed variation also significantly increase the sensation of bumpiness ($p < .05$). Slip profiles with speed variations were considered "bumpier" than others. With the speed variation, participants associated their experience to the cloth materials, such as "silk," "denim," or "linen." Some participants explain that they felt like their fingertip was "*slightly moving up and down [P1, P3, P11],*" as if their fingers were sliding through a creased fabric. This feedback also echoes previous findings on lateral-force-based textures on the tablet [56]. Interestingly, increasing relative speed also significantly increases the bumpiness score. Participants reported that the sanded dots of the ball "*became much more perceivable when the speed increased [P1],*" making the dots feel bumpier.

The results indicate that coupling with hand motions, varying relative slip speed and speed variations could alter the tactile perception of participants. When developing applications for this type of haptic feedback, designers need to control the slip applied on users' fingers. Therefore, it is important to know the minimum change in slip that users can detect. This knowledge provides necessary insights into the development of slip patterns, hardware implementations, and applications.

STUDY2: DISCRIMINATION THRESHOLD OF SLIP SPEED

This study's goal is to explore the discrimination threshold of slip speed during midair hand movements. That is to say, given a combination of kinesthetic (*i.e.*, hand motion) and tactile feedback (*i.e.*, relative slip speed), how precise can users differentiate the slip speeds? This study's results help us to design distinguishable slip patterns for active exploration. For example, given a certain exploration speed, how can a sticky surface be perceived as even stickier, or how to create detectable bumps on a rough surface, etc.

Design

This experiment applied a 2×3 within-subject factorial design. The independent variables were *Exploration Speed* of hand and *Relative Slip Speed* of the ball. We selected two exploration speeds, 50mm/s and 70mm/s. As for the relative slip speeds, $\pm 60\%$ and 0% (*i.e.*, relatively slower than, relatively faster than, or equally fast to the hand motions) were selected.

This experiment uses a three-alternative forced-choice paradigm. Each combination consists of a series of blocks, in each block, three trials are presented, two with the reference relative speed (S) and one with the test relative speed ($S \pm \Delta S$). In the reference trial, the magnitude of S was one of the three relative slip speeds; the relative slip speed of test trial was either greater or smaller than the reference trial by ΔS. The value of ΔS was determined adaptively, as described shortly hereafter. Participants were asked to identify the test trial; the one which they feel is dissimilar from the others. The order of the test and reference trials was random for each block.

For determining the value of ΔS, a one-up-two-down adaptive staircase procedure was used. The reference S was set to be upper +60%, 0% or lower -60% from the exploration speed.

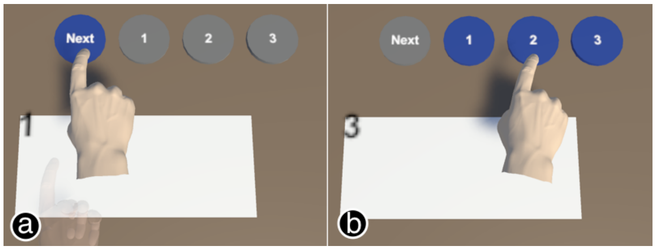

Figure 7. The study environment in STUDY2.

The step size ΔS was initially set to 50% of the hand motion. One incorrect answer increases ΔS, and two consecutively correct responses decrease ΔS. For the first three reversals, ΔS is decreased or increased by 20% of the exploration speed, and by 5% for the remaining twelve reversals. The experiment finishes after six staircase runs are completed (2 motion speed × 3 relative speed). The order of the staircase runs were randomized among the participants.

Procedure

Before the start of the testing session, participants were asked to stand in a comfortable position wearing their VR headset and were instructed to use their dominant index finger to slightly press on the ball. As displayed in Figure 7, the VR environment was similar as that used for the explorative study. Like the explorative study, practice trials were conducted before the formal experiment. In VR, there is a white sheet on the table with the number of the trial (1, 2 or 3) shown on its upper left corner; a semi-transparent hand is suspended above the sheet. Four buttons, a next button and three selection buttons, were shown on the table with different colors indicating what button could then be activated. For each sheet, the participants were asked to experience the sheet and then press the “Next” button to go to the next sheet (Figure 7a). After experiencing the three sheets, the participants needed to press the number buttons to identify their choice (Figure 7b), and then proceed to the next trial. To eliminate the motor noise, participants wore headphones emitting white noise during the study. In general, participants conducted between 50 to 80 trials for each staircase while each staircase took between 15 to 20 minutes. Participants could take short breaks between the staircases.

Participants

Twelve participants (7 females) between the ages of 20 and 26 took part in this study. Four of them had had experience using VR headsets and controllers. All of them are right- handed with a normal sense of touch.

Result

The discrimination thresholds of the slip speeds are displayed in Table 1. The average from the last 10 reversals was calculated for each participant. The estimated discrimination threshold of slip speed for each combination of hand motion and relative slip speed was computed by averaging the thresholds of participants.

Relative Slip Speed	60% Slower	Equals to (0%)	60% Faster
Exploration Speed 50mm/s	7.89mm/s (SE:0.68mm/s) (15.78%)	13.36mm/s (SE:1.66mm/s) (26.71%)	18.97mm/s (SE:2.00mm/s) (37.94%)
Exploration Speed 70mm/s	11.57mm/s (SE:1.30mm/s) (16.53%)	17.07mm/s (SE:1.96mm/s) (24.39%)	21.77mm/s (SE:3.99mm/s) (31.09%)

Table 1. The average discrimination thresholds of slip speeds for each combination.

The results suggest that the discrimination thresholds increase with faster relative slip speeds. For example, with an exploration speed of 50mm/s, the threshold is 13.36mm/s at +0% relative speed and increases to 18.97mm/s at +60% relative speed. Such an observation is also valid when the exploration speed is 70mm/s. To examine how the thresholds were affected, we calculated a threshold / exploration speed ratio for each combination. We then conducted a repeated measures two-way ANOVA on the ratios with *Exploration Speed* and *Relative Slip Speed* as independent variables. The analyses shows no significant interaction between the two variables ($F_{1.879,20.667}$ = 1.734, p = .2). The *Exploration Speed* yields no significant difference ($F_{1.0,11.0}$ = 1.909, p = .195), which indicates the ratios stay relatively unchanged across the exploration speeds. The result is interesting, as it indicates that the designer could design different slip profiles based on the ratio of the exploration speed, and the profiles could be still valid with various exploration speeds. However, analysis shows that the *Relative Slip Speed* significantly affects the ratios ($F_{1.610,17.741}$ = 11.744, p <.001). The pairwise comparisons show that the ratios significantly increased with increasing relative slip speeds (all p <.05). These results indicate that profiles with faster relative speeds should be designed with larger speed variations for being discriminated, as we observed with the values of discrimination thresholds.

STUDY3: DISCRIMINATION THRESHOLD OF ANGLE

Ideally, the direction of a slip should be exactly the opposite to the direction of a hand movement. To achieve this, the slip angle needs to be instantly adjusted according to the motions. However, there are mechanical trade-offs introduced by the mechanical structure of slip display. When the slip direction changes, due to the user’s finger being placed on the ball, a *rotational slip* also occurs. Frequent rotational slips could result in undesirable haptic noise and reduce the quality of the user experience. This problem might worsen if accompanied by unsteady hand movements during midair operation. Also, in order to cope with sudden turns of finger motions, the motor used for changing slip directions should run at full steam. Higher motor speeds lead to less precise control of slip directions. Therefore, it is important to examine the discrimination threshold between the hand motion and the slip direction. This study’s results help us to set a proper threshold for changing the slip direction and mitigating the aforementioned issues caused by mechanical limitations. Although previous studies evaluate the perception of slip directions in grounded [54] and body-grounded conditions [8], the effect of hand motion

Relative Slip Speed	60% Slower	Equals to (0%)	60% Faster
Exploration Speed 50mm/s	51.96° (SE:5.41°)	53.10° (SE:5.05°)	53.82° (SE:6.61°)
Exploration Speed 70mm/s	51.43° (SE:6.06°)	54.26° (SE:5.74°)	56.73° (SE:5.26°)

Table 2. The average discrimination thresholds of slip angles for each combination.

on the perception of slip directions remains underexplored. This study aims at understanding the discrimination threshold of the slip angle given a combination of a hand motion and relative slip.

Design and Procedure

The experiment applied a 2 × 3 within-subject factorial design. The independent variables were *Exploration Speed* and *Relative Slip Speed*. Six discrimination thresholds were found for the *Exploration Speed* × *Relative Slip Speed* combinations. We used the same exploration speeds and relative slip speeds as the previous study.

This experiment uses a three-alternative forced-choice paradigm. Each combination consists of a series of blocks, in each block, three trials are presented, two with the reference angle (S) and one with the test angle (S±ΔS). In the reference trial, the magnitude of S is 180°, which represents the ball slipping in the opposite direction of the hand motion. The relative angle of test trial is either greater or smaller than the reference trial by ΔS. The value of ΔS was determined adaptively. The order of test and reference trial was random for each block.

A one-up-two-down adaptive staircase procedure is used. The step size ΔS was initially set to a random number between 50° to 90°. One incorrect answer increases ΔS, and two consecutively correct responses decrease ΔS. For the first three reversals, ΔS is decreased or increased by 15°, and by 5° for the remaining twelve reversals. The experiment finishes after six staircase runs are completed (2 for motion speed × 3 for relative speed). The order of the staircase runs were randomized among participants.

The procedures of this study are the same as those for the speed discrimination threshold study, except that participants are instructed to select the test angle from three trials. To avoid the rotational slip, participants are asked to raise their index finger up from the ball when their hand in VR ceased to “touch” the sheet, therefore, no rotational slip is perceived by the participants. Participants conducted between 50 to 80 trials for each staircase, each staircase took between 15 to 25 minutes.

Participants

Twelve participants (7 females) between the ages of 20 and 23 took part in this study. Six of them have experience using VR headsets and controllers. All of them are right- handed with a normal sense of touch.

Result

The average thresholds are shown in Table 2. ANOVA yields no significant effect of *Exploration Speed* ($F_{1.0,11.0}$ = .23, p = .641) and *Relative Slip Speed* ($F_{1.547,17.019}$ = .406, p = .621). There was also no significant effect of *Exploration Speed* × *Relative Slip Speed* ($F_{1.938,21.314}$ = .09, p = .909). The average thresholds across all the conditions is 49.90°. This result suggests that the change in the slip angle could be modified until the relative slip angle between the ball and the finger movements exceeds 53.55°. As a result, the slip direction does not need to strictly follow the hand motion.

When compared to previous studies of directional sensitivity of the fingertip[13], our results show lower sensitivity. One possible reason is that human beings are more sensitive to directional skin stretch than slip[30]. Participants might be further distracted by the hand motions and visual feedback in VR. Interestingly, the explanation echoes that of previous works where their devices generate only 1-DoF skin stretch [59] or 1-DoF slip [55] for the 2-DoF active finger exploration. Although, their works indicate that the 1-DoF directional stimuli were acceptable for an arbitrary relative motion between finger and surface, our results suggest that 2-DoF slip may create more coherent sensations of sliding. In addition, these results are important for mitigating the undesired rotational slip during the active exploration, and will make application development easier.

DEMO APPLICATION AND TESTING

To demonstrate the capabilities of our RollingStone prototype, we created three applications. Based on our psychophysical study results, various slip profiles were pre-designed for these applications. The desired relative slip speeds are calculated by hand motion speed multiplied by a percentage number per each profile accordingly. The slip angle changes only when the moving direction of the hand exceeds 50°, mitigating unnatural rotational slip during the finger’s exploration. All applications were developed using the Unity3D game engine, and are integrated with the VIVE developing environment and tracking system.

Decorating the Room

This application highlights the ability of RollingStone to render numerous haptic profiles. As displayed in Figure 8a, we designed a set of textures based on previous study results. These textures are demonstrated in a virtual bedroom, where users may move their fingers across the surfaces of the furniture. Initially, all furniture surfaces were shaded grey and lack any textures. To “decorate” the bedroom, the user may navigate the bedroom, select a piece of furniture, and assign it a texture. For instance, after a user selected a table, a list of textures, such as plastic, wood, or leather, are shown. Each texture is pre-defined by the authors. The user selects a texture from the list and assigns that texture to the selected piece of furniture. Thereafter, the user could “feel” that texture by moving the RollingStone prototype on the furniture.

Escaping from the Room

In this application, users are given the goal of virtually escaping from a locked room by finding a secret book on a

Figure 8. RollingStone Applications: (a) Decorating the Room, (b) Escaping from the Room, and (c) Ninja Survival.

bookshelf. The user is instructed to escape from the room by pressing on the cover of a secret book, pressing it further back into its shelf. Users need to slide their finger across the book covers and find the book cover that they perceive to be the most "sticky." As displayed in Figure 8b, during the navigation, the system creates bumpiness sensations when the user's finger traverses gaps between each book cover. The system increases the adhesiveness of the book cover when the user's finger "touches" the secret book's cover. Finally, by pushing on the secret book, the bookshelf is moved aside, exposing a trap door behind the bookshelf.

Ninja Survival

Our Ninja Survival app aims at demonstrating the additional capabilities of our RollingStone prototype: short-term or rotational slips. In the virtual environment, the user is surrounded by approaching enemies and needs to defend themselves by throwing darts at these assailants. Users will sense both short-term and rotational slips when throwing the darts. Similar to previous slip profiles, we further designed the rotational slip profiles to simulate different types of darts.

Preliminary User Evaluation Study

We conducted a preliminary user evaluation using our prototype to assess user approval of the RollingStone concept. The aim of this study is to ensure if the slip feedback generated by RollingStone is a valuable haptic addition.

Participants

We recruited 12 participants (4 females) between ages of 20 and 28 to participate in the study. All participants had a normal sense of touch.

Experimental Design and Procedure

This experiment is designed to measure the user's enjoyment of RollingStone in comparison to use without haptic feedback. Participants had the opportunity to experience the three aforementioned games using the RollingStone prototype. For comparison, they also experienced use of the same applications without slip. Without the slip feedback, the participants were instructed to play the three games with only visual feedback, for example, assigned a texture to the furniture, push the books one by one until they found the secret book, or throwing the darts by waving the controller. The conditions with and without haptic feedback were counter-balanced among participants. They could use the applications as many times as they wanted. After this study, participants completed a questionnaire asking for agreement ratings on the *Realism* and *Enjoyment* during the applications. Ratings were made using a continuous numeric scale from 1 to 7, with 1 indicating "strongly disagree" and 7 "strongly agree." Decimal ratings such as 5.8 were permitted. The order of applications were randomly assigned to every participant. The entire experiment took about 30 minutes.

Result and Discussion

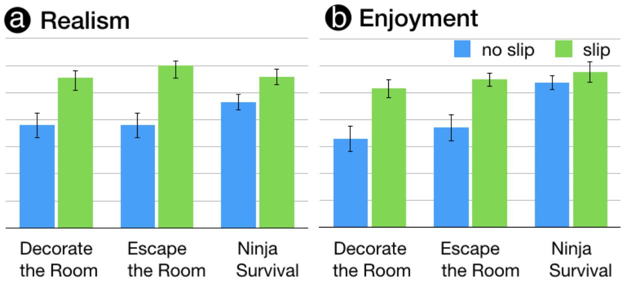

Figure 9. Agreement scores in regard to (a) Realism and (b) Enjoyment.

The subjective ratings on realism and enjoyment were analyzed using a t-test.

Realism. As displayed in Figure 9a, for all applications, the slip feedback received scores in realism significantly higher than the no-slip condition (all $p < .05$). For Decorating the Room, participants reported that it is realistic to "*feel different textures right away with RollingStone [P3].*" However, there was also one participant who gave a lower score (less than 4) to RollingStone, as he reported *"the experiences of textures were not coherent to the visual feedback [P6]."* Although the participant could differentiate the virtual textures, his feedback indicates that future designers should carefully utilize slip in regard to the specific visual feedback, otherwise the realism might be degraded. Another participant who was an engineer of haptic techniques suggested that "it would be better if the controller provided both slip and vibrotactile feedback [P7]," suggesting that multimodal tactile feedback could further enhance the realism of virtual textures. Almost all participants like the slip feedback during escaping from the room, since they found "*the sensations of the gaps between books makes this game much more realistic [P7, P11].*" Finally, the Ninja Survival received the average score above 5.5, showing that the rotational slip is also a potential tactile feedback to create more realistic VR experiences. In general, participants reported that the rotational slip helped them such that they *"felt the weights and types of the darts [P1, P11]."*

Enjoyment. As shown in Figure 9b, participants found it an enjoyable experience when they felt the slip feedback. The average scores of the three applications are all above 5. RollingStone received significantly higher scores than the no-slip condition in Decorating the Room and Escaping from the Room (both p < .05). For Decorating the Room, one participant reported that "*this is just what I want in Ikea [P1]!*" For Escaping from the Room, most of the participants agreed that "*the slip feedback makes the escaping process more exciting and immersive [P1, P7, P12].*" Interestingly, RollingStone did not receive significantly higher enjoyment scores in Ninja Survival (p = .56). Although participants agreed the rotational slip enhanced the realism of throwing darts, they also felt that the slip feedback is incremental for the enjoyment. Two partcipants reported that "*the slip feedback was not important*" and they "*preferred to receive the vibrotactile feedback when the dart hit the zombies, just like they had felt on console controllers [P4, P12].* " Their feedback indicates that conventional haptic feedback is still crucial for game experience.

DISCUSSION AND LIMITATIONS

Limitations of Psychophysical Studies. In this paper, we decided to conduct a fundamental study examining the factors of hand motion and relative slip speed for discrimination thresholds of slip speeds and slip angles. While the knowledge we obtained is limited by the two factors, we were able to apply the information learned when implementing prototype applications. Future work will extend our studies to multiple directions of hand movements and the levels of normal forces of fingers. Furthermore, current studies only discussed slips with straight hand movements. Another research direction is to examine users' capability to discriminate *rotational slip feedback*. A careful psychophysical study on rotational slip will be conducted. Lastly, a more general study comparing other feedback mechanisms is also needed, to better understand the tradeoffs and benefits of our approach.

Comfort. During our studies, some participants reported that high-speed slip feedback degraded the comfort since the friction force is stinging. This feedback informs us that the material of the ball should be carefully examined regarding different slip speeds, especially for highly rough materials.

Texture Rendering Algorithm. This study focuses on exploring the discrimination thresholds of the slip speed and the slip angle. In addition, the slip profiles used in the applications were pre-defined and fine-tuned by the authors. Like previous works on lateral-force-based textures [25, 56], to enable more robust implementation of virtual textures, it is crucial to design a tactile rendering algorithm that automatically generates the relative slip speeds. Our next step is to explore rendering algorithms suitable for our purpose.

User Experience. Compared to some slip feedback devices[55], RollingStone uses a relative small ball size. The size of the ball and the aperture of the hollow are identical to Webster *et al.* [54]. It is a trade-off, since increasing the size can significantly increase the size and the weight of the prototype. Although the roundness of the surface of the ball can be perceived, combined with visual feedback and hand motions, most of the participants perceived that they are sliding their finger on a flat virtual surface. In addition, the design of the arc-shaped edge of the hole comes from our early prototype iteration, in which users reported that the sharp edge of the hole not only interfered with their perception but also was uncomfortable. Using our current design, we did not receive any negative feedback on the edge. Still, a finger rest could be designed into the device in the future.

Latency. Using current setup and device, delays between hand movements and the haptic feedback do exist. During motion reversals, the average latency between hand motion and the device is 235 ms; when the taxel is rotated, the average latency between hand motion and haptic feedback is 260 ms. Efforts will be taken to optimize the calculation algorithm and communications in the future.

Limitations of Exploratory Studies. In our exploratory study, we aimed at exploring how slip parameters impact the perception of texture properties. Although we did not evaluate the realism of virtual textures, what we learned provides a guideline for future design of slip profiles. A future work could further use control group such as real textures comparing a list of designed textures, evaluating the effectiveness of the virtual textures.

CONCLUSION

Our work introduces RollingStone, a VR controller that uses a *single* 2-DoF slip tactile pixel to produce sensations of finger sliding and textures. Based on our RollingStone prototype, several user studies were conducted. In an explorative study, we discussed the subjective perception of this type of slip feedback with six pre-defined slip profiles, and ensured that changing the relative motion between the finger and the ball could alter the perceptions conveying the properties of a texture. The following two psychophysical studies reveal that slip profiles could be designed by considering the ratio of the exploration speed of hands, and the discrimination threshold of the relative slip angle is about 50% across all tested conditions. In the preliminary user study, we evaluated the capabilities of RollingStone via implementation into three VR games. The subjective scores indicate that most of the participants considered that the slip feedback generated by RollingStone is valuable for the experiences of realism and enjoyment in VR. Their feedback also indicates that multimodal haptic feedback and conventional vibrotactile feedback could further enhance their the experiences. More future works will focus on examining these observations.

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REFERENCES

1. Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison. 2010. TeslaTouch: Electrovibration for Touch Surfaces. In *Proceedings of the 23Nd Annual ACM Symposium on User Interface Software and Technology (UIST '10)*. ACM, New York, NY, USA, 283–292. `DOI:` `http://dx.doi.org/10.1145/1866029.1866074`

2. Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. NormalTouch and TextureTouch: High-fidelity 3D Haptic Shape Rendering on Handheld

Virtual Reality Controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 717–728. DOI: `http://dx.doi.org/10.1145/2984511.2984526`

3. Mourad Bouzit, Grigore Burdea, George Popescu, and Rares Boian. 2002. The Rutgers Master II-new design force-feedback glove. *IEEE/ASME Transactions on mechatronics* 7, 2 (2002), 256–263.
4. Carissa J Cascio and K Sathian. 2001. Temporal cues contribute to tactile perception of roughness. *Journal of Neuroscience* 21, 14 (2001), 5289–5296.
5. Inrak Choi, Heather Culbertson, Mark R. Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 119–130. DOI: `http://dx.doi.org/10.1145/3126594.3126599`
6. Inrak Choi, Elliot W Hawkes, David L Christensen, Christopher J Ploch, and Sean Follmer. 2016. Wolverine: A wearable haptic interface for grasping in virtual reality. In *Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on*. IEEE, 986–993.
7. Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM.
8. Minwoo Choi and Gerard Jounghyun Kim. 2009. TouchBall: A Design and Evaluation of a Hand-held Trackball Based Touch-haptic Interface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 1535–1538. DOI: `http://dx.doi.org/10.1145/1518701.1518936`
9. Heather Culbertson, Samuel B. Schorr, and Allison M. Okamura. 2018. Haptics: The Present and Future of Artificial Touch Sensation. *Annual Review of Control, Robotics, and Autonomous Systems* 1, 1 (2018), null. DOI:`http://dx.doi.org/10.1146/annurev-control-060117-105043`
10. Heather Culbertson, Julie M Walker, and Allison M Okamura. 2016. Modeling and design of asymmetric vibrations to induce ungrounded pulling sensation through asymmetric skin displacement. In *Haptics Symposium (HAPTICS), 2016 IEEE*. IEEE, 27–33.
11. David Escobar-Castillejos, Julieta Noguez, Luis Neri, Alejandra Magana, and Bedrich Benes. 2016. A review of simulators with haptic devices for medical training. *Journal of medical systems* 40, 4 (2016), 104.
12. Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: Dynamic Physical Affordances and Constraints Through Shape and Object Actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 417–426. DOI: `http://dx.doi.org/10.1145/2501988.2502032`
13. Brian T Gleeson, Scott K Horschel, and William R Provancher. 2009. Communication of direction through lateral skin stretch at the fingertip. In *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*. IEEE, 172–177.
14. CyberGrasp Glove. 2016. CyberGlove Systems Inc. (2016).
15. Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1991–1995. DOI: `http://dx.doi.org/10.1145/2858036.2858487`
16. Sidhant Gupta, Tim Campbell, Jeffrey R. Hightower, and Shwetak N. Patel. 2010. SqueezeBlock: Using Virtual Springs in Mobile Devices for Eyes-free Interaction. In *Proceedings of the 23Nd Annual ACM Symposium on User Interface Software and Technology (UIST '10)*. ACM, New York, NY, USA, 101–104. DOI: `http://dx.doi.org/10.1145/1866029.1866046`
17. Vincent Hayward and M Cruz-Hernandez. 2000. Tactile display device using distributed lateral skin stretch. In *Proceedings of the haptic interfaces for virtual environment and teleoperator systems symposium*, Vol. 69. ASME, 1309–1314.
18. Colin Ho, Jonathan Kim, Sachin Patil, and Ken Goldberg. 2015. The Slip-Pad: A haptic display using interleaved belts to simulate lateral and rotational slip. In *World Haptics Conference (WHC), 2015 IEEE*. IEEE, 189–195.
19. Mark Holliins, Richard Faldowski, Suman Rao, and Forrest Young. 1993. Perceptual dimensions of tactile surface texture: A multidimensional scaling analysis. *Perception & psychophysics* 54, 6 (1993), 697–705.
20. Hisayoshi Honda, Shinichi Hirai, and others. 2016. Development of a novel slip haptic display device based on the localized displacement phenomenon. *IEEE Robotics and Automation Letters* 1, 1 (2016), 585–592.
21. Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: Adding Haptic Surface to Graphics. In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '01)*. ACM, New York, NY, USA, 469–476. DOI: `http://dx.doi.org/10.1145/383259.383314`

22. RS Johansson and G Westling. 1984. Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental brain research* 56, 3 (1984), 550–564.
23. Rebecca P Khurshid, Naomi T Fitter, Elizabeth A Fedalei, and Katherine J Kuchenbecker. 2017. Effects of grip-force, contact, and acceleration feedback on a teleoperated pick-and-place task. *IEEE transactions on haptics* 10, 1 (2017), 40–53.
24. Johan Kildal. 2010. 3D-press: Haptic Illusion of Compliance when Pressing on a Rigid Surface. In *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction (ICMI-MLMI '10)*. ACM, New York, NY, USA, Article 21, 8 pages. `DOI:` `http://dx.doi.org/10.1145/1891903.1891931`
25. Seung-Chan Kim, Ali Israr, and Ivan Poupyrev. 2013. Tactile Rendering of 3D Features on Touch Surfaces. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 531–538. `DOI:` `http://dx.doi.org/10.1145/2501988.2502020`
26. Daniel Leithinger, Sean Follmer, Alex Olwal, and Hiroshi Ishii. 2014. Physical Telepresence: Shape Capture and Display for Embodied, Computer-mediated Remote Collaboration. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 461–470. `DOI:` `http://dx.doi.org/10.1145/2642918.2647377`
27. Thomas H Massie, J Kenneth Salisbury, and others. 1994. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, Vol. 55. Citeseer, 295–300.
28. Joe Mullenbach, Dan Johnson, J Edward Colgate, and Michael A Peshkin. 2012. ActivePaD surface haptic device. In *Haptics Symposium (HAPTICS), 2012 IEEE*. IEEE, 407–414.
29. Takaaki Nara, Masaya Takasaki, Susumu Tachi, and Toshiro Higuchi. 2000. An application of SAW to a tactile display in virtual reality. In *Ultrasonics Symposium, 2000 IEEE*, Vol. 1. IEEE, 1–4.
30. Ulf Norrsell and Hakan Olausson. 1994. Spatial cues serving the tactile directional sensibility of the human forearm. *The Journal of physiology* 478, 3 (1994), 533–540.
31. Shogo Okamoto, Hikaru Nagano, and Yoji Yamada. 2013. Psychophysical dimensions of tactile perception of textures. *IEEE Transactions on Haptics* 6, 1 (2013), 81–93.
32. Ayberk Ozgur, Wafa Johal, and Pierre Dillenbourg. 2016. Permanent magnet-assisted omnidirectional ball drive. In *Proceedings of the 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE.
33. Claudio Pacchierotti, Stephen Sinclair, Massimiliano Solazzi, Antonio Frisoli, Vincent Hayward, and Domenico Prattichizzo. 2017. Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives. *IEEE transactions on haptics* 10, 4 (2017), 580–600.
34. Jérôme Pasquero and Vincent Hayward. 2003. STReSS: A practical tactile display system with one millimeter spatial resolution and 700 Hz refresh rate. In *Proc. Eurohaptics*, Vol. 2003. 94–110.
35. Alvaro G Perez, Daniel Lobo, Francesco Chinello, Gabriel Cirio, Monica Malvezzi, José San Martín, Domenico Prattichizzo, and Miguel A Otaduy. 2015. Soft finger tactile rendering for wearable haptics. In *World Haptics Conference (WHC), 2015 IEEE*. IEEE, 327–332.
36. Ivan Poupyrev, Tatsushi Nashida, and Makoto Okabe. 2007. Actuation and Tangible User Interfaces: The Vaucanson Duck, Robots, and Shape Displays. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction (TEI '07)*. ACM, New York, NY, USA, 205–212. `DOI:` `http://dx.doi.org/10.1145/1226969.1227012`
37. Domenico Prattichizzo, Francesco Chinello, Claudio Pacchierotti, and Monica Malvezzi. 2013. Towards wearability in fingertip haptics: a 3-dof wearable device for cutaneous force feedback. *IEEE Transactions on Haptics* 6, 4 (2013), 506–516.
38. William R Provancher and Nicholas D Sylvester. 2009. Fingerpad skin stretch increases the perception of virtual friction. *IEEE Transactions on Haptics* 2, 4 (2009), 212–223.
39. Jun Rekimoto. 2013. Traxion: A Tactile Interaction Device with Virtual Force Sensation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 427–432. `DOI:` `http://dx.doi.org/10.1145/2501988.2502044`
40. Satoshi Saga and Ramesh Raskar. 2013. Simultaneous geometry and texture display based on lateral force for touchscreen. In *World Haptics Conference (WHC), 2013*. IEEE, 437–442.
41. Mark Salada, J Edward Colgate, MV Lee, and Peter Vishton. 2002a. Fingertip haptics: A novel direction in haptic display. In *Proceedings of the 8th mechatronics forum international conference*. University of Twente, 1211–1220.
42. Mark Salada, J Edward Colgate, Peter Vishton, and Eviatar Frankel. 2005. An experiment on tracking surface features with the sensation of slip. In *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*. IEEE, 132–137.

43. Mark Salada, Peter Vishton, J Edward Colgate, and Eviatar Frankel. 2004. Two experiments on the perception of slip at the fingertip. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004. HAPTICS'04. Proceedings. 12th International Symposium on*. IEEE, 146–153.

44. Mark A Salada, J Edward Colgate, Margaret V Lee, and Peter M Vishton. 2002b. Validating a novel approach to rendering fingertip contact sensations. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002. HAPTICS 2002. Proceedings. 10th Symposium on*. IEEE, 217–224.

45. Samuel B. Schorr and Allison M. Okamura. 2017. Fingertip Tactile Devices for Virtual Object Manipulation and Exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 3115–3119. DOI: **http://dx.doi.org/10.1145/3025453.3025744**

46. Alexa F. Siu, Eric J. Gonzalez, Shenli Yuan, Jason Ginsberg, Allen Zhao, and Sean Follmer. 2017. shapeShift: A Mobile Tabletop Shape Display for Tangible and Haptic Interaction. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17)*. ACM, New York, NY, USA, 77–79. DOI: **http://dx.doi.org/10.1145/3131785.3131792**

47. Massimiliano Solazzi, William R Provancher, Antonio Frisoli, and Massimo Bergamasco. 2011. Design of a SMA actuated 2-DoF tactile device for displaying tangential skin displacement. In *World Haptics Conference (WHC), 2011 IEEE*. IEEE, 31–36.

48. Paul Strohmeier, Jesse Burstyn, Juan Pablo Carrascal, Vincent Levesque, and Roel Vertegaal. 2016. ReFlex: A Flexible Smartphone with Active Haptic Feedback for Bend Input. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16)*. ACM, New York, NY, USA, 185–192. DOI: **http://dx.doi.org/10.1145/2839462.2839494**

49. Paul Strohmeier and Kasper Hornbæk. 2017. Generating Haptic Textures with a Vibrotactile Actuator. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. ACM, New York, NY, USA, 4994–5005. DOI: **http://dx.doi.org/10.1145/3025453.3025812**

50. Ian R Summers, Craig M Chanter, Anna L Southall, and Alan C Brady. 2001. Results from a Tactile Array on the Fingertip. In *Proceedings of Eurohaptics*, Vol. 2001.

51. Novint Technologies. 2018. (2018). **https://en.wikipedia.org/wiki/Novint_Technologies**

52. Nikolaos G Tsagarakis, T Horne, and Darwin G Caldwell. 2005. Slip aestheasis: A portable 2d slip/skin stretch display for the fingertip. In *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*. IEEE, 214–219.

53. Ramiro Velazquez, Edwige E Pissaloux, Moustapha Hafez, and Jérôme Szewczyk. 2008. Tactile rendering with shape-memory-alloy pin-matrix. *IEEE Transactions on Instrumentation and Measurement* 57, 5 (2008), 1051–1057.

54. Robert J. Webster, III, Todd E. Murphy, Lawton N. Verner, and Allison M. Okamura. 2005. A Novel Two-dimensional Tactile Slip Display: Design, Kinematics and Perceptual Experiments. *ACM Trans. Appl. Percept.* 2, 2 (April 2005), 150–165. DOI: **http://dx.doi.org/10.1145/1060581.1060588**

55. Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. 2018. Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM.

56. Laura Winfield, John Glassmire, J Edward Colgate, and Michael Peshkin. 2007. T-pad: Tactile pattern display through variable friction reduction. In *EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint*. IEEE, 421–426.

57. Juan Wu, Na Li, Wei Liu, Guangming Song, and Jun Zhang. 2015. Experimental study on the perception characteristics of haptic texture by multidimensional scaling. *IEEE transactions on haptics* 8, 4 (2015), 410–420.

58. Vibol Yem, Ryuta Okazaki, and Hiroyuki Kajimoto. 2016a. FinGAR: Combination of Electrical and Mechanical Stimulation for High-fidelity Tactile Presentation. In *ACM SIGGRAPH 2016 Emerging Technologies (SIGGRAPH '16)*. ACM, New York, NY, USA, Article 7, 2 pages. DOI: **http://dx.doi.org/10.1145/2929464.2929474**

59. Vibol Yem, Mai Shibahara, Katsunari Sato, and Hiroyuki Kajimoto. 2016b. Expression of 2DOF Fingertip Traction with 1DOF Lateral Skin Stretch. In *International AsiaHaptics conference*. Springer, 21–25.

60. Andre Zenner and Antonio Kruger. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 23, 4 (April 2017), 1285–1294. DOI: **http://dx.doi.org/10.1109/TVCG.2017.2656978**