SpinOcchio: Understanding Haptic-Visual Congruency of Skin-Slip in VR with a Dynamic Grip Controller

Myung Jin Kim
Industrial Design, KAIST
Daejeon, Republic of Korea
dkmj@kaist.ac.kr

Neung Ryu
Industrial Design, KAIST
Daejeon, Republic of Korea
n.ryu@kaist.ac.kr

Wooje Chang
Industrial Design, KAIST
Daejeon, Republic of Korea
wooje.chang@kaist.ac.kr

Michel Pahud
Microsoft Research
Redmond, WA, United States
mpahud@microsoft.com

Mike Sinclair
Microsoft Research
Redmond, WA, United States
sinclair@microsoft.com

Andrea Bianchi
Industrial Design, KAIST
Daejeon, Republic of Korea
andrea@kaist.ac.kr

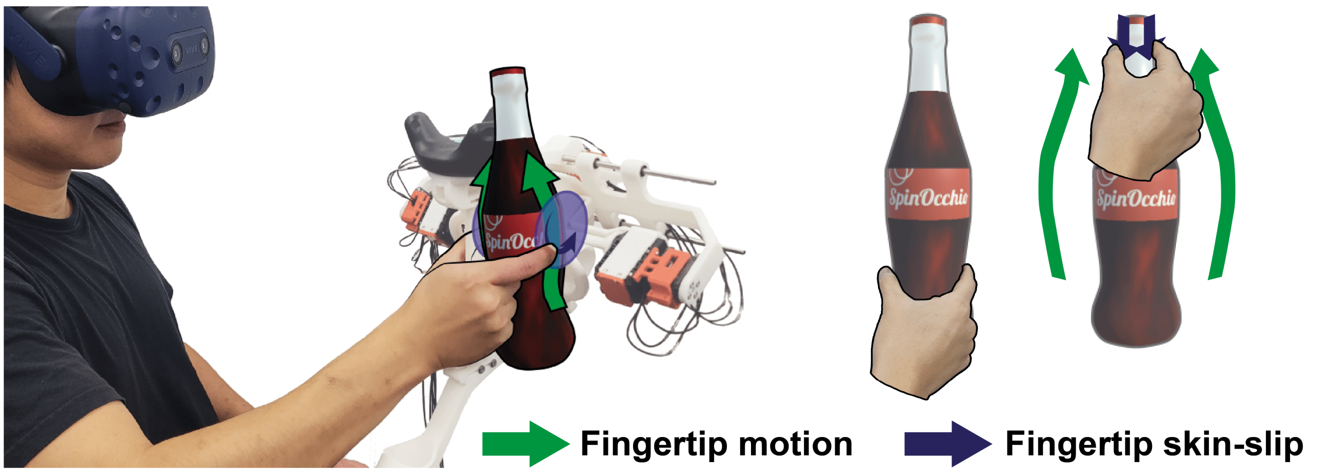

Figure 1: (Left) The spinning discs of *SpinOcchio* in contact with the fingertips enable the user to feel the moving surface of a virtual bottle as it slides through their fingertips. The overlay of the virtual bottle was added in post-production for visualization. (Right) When lifting the hand while holding *SpinOcchio,* downward skin-slip feedback applied to each fingertip with varying grip widths simulates the sensation of a stationary bottle slipping between the fingers.

ABSTRACT

This paper's goal is to understand the haptic-visual congruency perception of skin-slip on the fingertips given visual cues in Virtual Reality (VR). We developed *SpinOcchio* (*Spin* for the spinning mechanism used, *Occhio* for the Italian word "eye"), a handheld haptic controller capable of rendering the thickness and slipping of a virtual object pinched between two fingers. This is achieved using a mechanism with spinning and pivoting disks that apply a tangential skin-slip movement to the fingertips. With *SpinOcchio*, we determined the baseline haptic discrimination threshold for skin-slip, and, using these results, we tested how haptic realism of motion and thickness is perceived with varying visual cues in VR. Surprisingly, the results show that in all cases, visual cues dominate over haptic perception. Based on these results, we suggest applications that leverage skin-slip and grip interaction, contributing further to realistic experiences in VR.

CHI '22, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9157-3/22/04…$15.00
https://doi.org/10.1145/3491102.3517724

CCS CONCEPTS

• **Hardware** → **Haptic devices**; • **Human-centered computing** → **Haptic devices**; **Virtual reality**; *User studies.*

KEYWORDS

Haptics, skin-slip, normal force, controller, Virtual Reality

ACM Reference Format:

Myung Jin Kim, Neung Ryu, Wooje Chang, Michel Pahud, Mike Sinclair, and Andrea Bianchi. 2022. SpinOcchio: Understanding Haptic-Visual Congruency of Skin-Slip in VR with a Dynamic Grip Controller . In *CHI Conference on Human Factors in Computing Systems (CHI '22), April 29-May 5, 2022, New Orleans, LA, USA*. ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3491102.3517724

1 INTRODUCTION

Experience in Virtual Reality (VR) is greatly enhanced through various sensory feedback that come together to form a congruent experience that is believable and is becoming increasingly difficult to distinguish from reality. Notably, there have been considerable efforts to render the sense of touch in VR using tactile and kinesthetic haptic feedback congruent with visuals, enabling one to touch[3, 12], hold [7, 8], brush with fingertip[25, 26, 39], and manipulate[9, 35] virtual objects with increased levels of realism and immersion.

Oftentimes, however, prior works have found that the haptic-visual congruence is a less important factor in experiencing VR [32, 41], especially in the presence of strong visual cues or when trying to determine the direction of skin-deformations [41]. A great example of this is the *Haptic Revolver* [39], a device capable of generating 1-DOF skin-slip on the fingertip to express relative movement. In the paper, the authors found that the direction of skin-slip had little impact on the perceived realism and that only a few participants were even capable of noticing slip forces rendered in the reverse direction of the visuals. The *Haptic Revolver* serves as a strong inspiration for our paper, both by convincing us that skin-slip has untapped potentials for creating novel realistic tactile illusions in 6-DOF and by leaving us questioning whether similar visuo-haptic incongruence would occur even if two opposing fingers (i.e., a grip) were to be stimulated instead of a single one.

We acknowledge this gap and designed *SpinOcchio* (*Spin* for the spinning mechanism used, *Occhio* for the Italian word "eye"), a handheld haptic device that creates the cutaneous sensation of skin-slip in VR by stimulating the opposing fingertips with tangential and normal forces applied to the fingertips. Ultimately, a two-finger skin slip would allow people to discover the shape of an object and some of the features of its surface via a continuous stroke – like exploring the profile of a glass bottle or a paper cup gripped between fingers (Figure 1). Using *SpinOcchio*, we evaluate the perceptual threshold of skin-slip rendered on both a single finger and two fingers forming a grip. We then conduct an in-VR study exploring the haptic-visual congruence perception of relative skin-slip directions, followed by a third evaluation of skin-slip combined with normal forces (i.e., dynamically changing grip width) in an unconstrained VR environment.

In summary, our contributions are as follows:

(1) We propose a new technique for delivering the sensation of surfaces slipping between opposing fingertips, using cutaneous force-feedback for a real-time speed-control loop
(2) We measure the discrimination threshold of tangential skin-slip directions for two opposing fingers when gripping an object, showing results aligned with those in prior work (54.90°).
(3) We explore the haptic-visual congruence perception in VR of skin-slip with different directions, objects, haptic mappings, and hand movements, demonstrating that visuals strongly affected the perception of skin-slip for two fingers
(4) We test user perception of the technique in VR with dynamic grip width change involved, finding that skin-slip and visuals affected the perception of normal forces

2 RELATED WORKS

SpinOcchio builds on previous works in two main domains: VR haptic devices that apply skin deformations and haptic-visual congruence.

2.1 VR Haptic Devices using Skin Deformation

Previous works focusing on rendering tactile haptic feedback on the fingertips using moving surfaces for interaction in VR are especially relevant to our research. Such fingertip cutaneous haptic feedback can be categorized in terms of tangential movement relative to the fingertips: touch with no tangential movement (normal forces), touch with limited tangential movement (skin shear and stretch), and touch with continuous tangential movement (skin-slip).

2.1.1 Normal Forces. Various prior works have applied normal forces to the fingertips to simulate the proprioceptive sensation of touching or grabbing virtual objects. Both NormalTouch and TextureTouch[3] apply normal forces to the index fingertip to render contact surface orientation and gross surface structures, respectively. Works involving normal forces on multiple fingers, such as Wolverine[8], CLAW[9], and CapstanCrunch[35], enable multi-finger interactions, such as touching and grasping rigid and compliant objects in VR.

Other works have applied normal forces to the entire hand for in-VR interactions using different techniques, such as solenoids inside the handle to poke the hand for directional and tactile cues (HapticVec[6]), active pin array in the hand to render 2.5D shapes (Pocopo[42]), wearable pivoting mass in the hand to grasp and throw virtual objects (Haptic PIVOT[22]), and sets of wires and brakes to give counterforce feedback when the hand encounters virtual surfaces (Wireality[12]).

2.1.2 Skin-Stretch. Skin-stretch feedback also has been explored as a technique to simulate sensations of weight and inertia of virtual objects and body parts. As skin-stretch devices require constant contact with the skin, they are commonly seen in a wearable form factor. Such devices have taken various approaches such as sliding belts worn on the thumb and index fingers to simulate a virtual object's weight (GravityGrabber[27]), vibrating 2D tactor worn on the index to simulate compliance experienced through the fingertip (HapCube[21]), and multi-finger wearable with asymmetrical skin stretch via voice coil actuators for simulating different weights in VR(Grabity[7]). One notable work by Provancher[30] applied in-hand skin stretch in not a wearable but a handheld form factor, using four sliding tactors surrounding the handle to render force and torque cues for immersive VR experiences.

Applying skin-stretch to other parts of the body have been explored as well. These explorations include stretching the forearm and shifting the center of gravity to simulate arm elongation in VR (Gum-Gum Shooting[40]), stretching the skin around the eyes while wearing an HMD to enable interactions of collisions, inertia, and directional cues (Masque[37]), and stretching the calves to simulate pulling, grazing, or fluid flow experienced through the legs in VR (Gaiters[38]).

2.1.3 Skin-Slip. Compared to other skin-deformation techniques, few works have explored the use of skin-slip to enable interactions in VR. These works all focused on rendering various surface texture properties when exploring virtual environments with the index finger. Haptic Revolver[39] uses an interchangeable actuated cylinder that is raised or lowered under the finger to render contact with a virtual surface and spins orthogonal to the index fingertip to render shear and slip forces on the fingertip. The authors explore interactions with and perceptions of contact surfaces through 1D motion. RollingStone[25] uses a rotating sphere to generate 2-DoF motions to simulate different textures and surface movements. Authors explore the perception of skin-slip speed and angle together with texture perception. ENTROPiA[26] uses a rotating end-effector attached to a robot arm that follows the fingertip to render encounter-type infinite surfaces through skin-slip.

Unlike the prior works above, *SpinOcchio* can generate skin-slips of arbitrary direction (6-DOF), thickness, and speed on a single or two gripping fingers, creating the illusion of objects that slip with respect to the touching finger(s).

2.2 Haptic-Visual Congruence

In the Psychophysics domain, there have been continuous efforts to understand the effects of incongruent sensory information on human perception, especially in multimodality environments. Beginning with early work, research in this domain has investigated the dominance of one modality over another. These include effects of haptic-visual incongruency in object form perception (Rock and Victor[32]), visual dominance over touch even for a tactually experienced population (Power and Graham[29]), the dominance of visual over haptic cues in determining the precepts of perceived objects (Power[28]), and effect of sensory conflict awareness on shape perception (Bacon and Shaw[2]).

More recent works have explored the effect of haptic-visual congruence in various contexts. They include the investigation of how humans integrate visual and haptic information similar to a maximum-likelihood integrator, (Ernst et al.[11]), the loss of single-cue sensory information within but not between modalities when multiple cues are present (Hillis et al.[15]), the immunity to visual incongruency of body-centered haptic tasks compared to world-centered haptic tasks (Kaas et al.[18]), brain activity observations suggesting vision having a stronger role than touch in object recognition (Kassuba et al.[20]), and the extension of the perception of peripersonal space through nearby tools through congruent visuo-tactile stimuli (Sengül et al.[34]).

Additionally, other works have investigated the effect of sensory incongruency between modalities in virtual environments. These works include the exploration of the role of inter-modal integration in presence in VR (Biocca et al.[5]) and the investigation on the perception of synchronous and asynchronous visual-haptic stimuli in VR (Di Luca and Mahnan[10]).

In contrast with these works, this paper aims to understand, through a set of studies, how skin-slip tactile stimulation rendered using the haptic controller *SpinOcchio* is affected by the presence of visual cues in VR.

3 THE SPINOCCHIO CONTROLLER

SpinOcchio is a handheld haptic device that simulates the movement and width of an object slipping between two fingers forming a grip (e.g., index and thumb). Like skin-stretch [31], skin-slip also produces a deformation of the skin of the fingertips via a cutaneous tangential force that instills the sensation of continuous stroking. However, differently from stretch and shear, the sensation is a gentle continuous brush, rather than the sensation of having the skin steadily pulled in a direction with no slipping. While previous skin-slip devices which exploited belts [16] or rolling surfaces [25, 39] are limited in the degree of directions that can be rendered or work with only a single finger, *SpinOcchio* is capable of rendering continuous skin-slip in 6-DOF and varying normal forces (i.e. varying grip width sizes) applied to two fingers, allowing a user immersed in a VR environment to perceive an object translating or rotating along different axes (Figure 2).

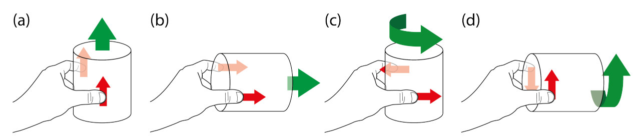

Figure 2: Translation and rotation movements in relation to fingertip skin-slip directions. (a) and (b) show the skin-slip direction on both fingertips matching the direction the object is translating. (c) and (d) show the skin-slip direction on both fingertips in opposite directions, reflecting the surface movement direction of rotating objects in relation to the fingertips.

3.1 Principles of operation

Skin-slip has two components: the **direction** of motion and its tangential **speed** (i.e., the rate at which the skin is brushed over the distance of the motion). These are achieved using a pair of spinning disks (one per finger), each attached to pivoting motor. To understand the principles of operations, consider the diagram in Figure 3.

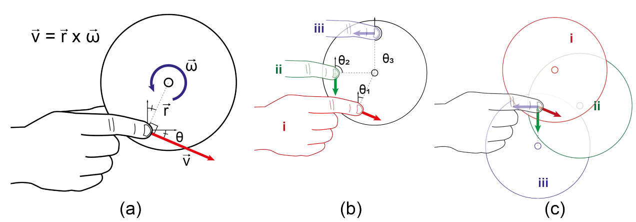

Figure 3: The spinning pivoting disk mechanism of *SpinOcchio*. (a) Skin-slip speed determined by disk spin speed. (b) Direction of skin-slip determined by relative position of fingertip to disk center. (c) Displacing the disk instead of the finger to change skin-slip direction at the point of contact.

Imagine placing a finger on the surface of a disk of radius $\vec{r}$ which spins with an angular velocity of $\vec{\omega}$. The resulting cutaneous skin-slip deformation has an intensity of $\vec{V} = \vec{r} \times \vec{\omega}$ applied in the direction that is perpendicular to $\vec{r}$, as in Figure 3(a). Therefore, touching different locations near the outside edge of the disc results in skin-slip with different directions, while changing the speed of the rotating disk changes the perceived speed of the disk. *SpinOcchio* leverages this intuition for generating skin-slip forces of varying magnitude and direction. It uses a pair of motors to pivot the spinning disks and therefore control the exact position where the users' fingertips are placed, resulting in predictable $\vec{V}$ values (Figure 3(c)). It is important to note that, in practice, it is not possible to pivot the spinning disks 360° because it would otherwise collide against the user's hand. *SpinOcchio* therefore combines 180° pivoting with clockwise and anticlockwise spinning direction to render skin-slip in all 360°.

In conclusion, *SpinOcchio*'s disks can spin in either direction and at different speeds, allowing it to render skin-slip of varying direction and speeds independently on one or two fingertips. Furthermore, the distance between the disks can also dynamically increase or decrease, resulting in normal forces applied to the fingertips (Figure 4). When combined with visual stimuli, these forces can be interpreted as translations or rotations along the surface of 3D objects of different widths.

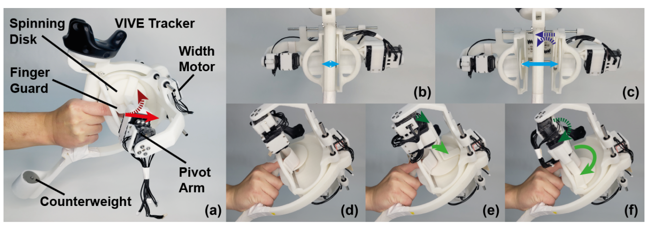

Figure 4: The *SpinOcchio* prototype and its operating parts. (a) Disk speed determines speed of skin-slip. (b-c) Width-changing motors adjust distance between the opposing disks through rack and pinion gears. (d-f) Disk pivots in a 180° range.

3.2 Implementation

SpinOcchio consists of two pivoting spinning disc modules, a set of width-change actuators, and a VIVE tracker, all mounted on a handheld housing (Figure 4). Each disc module consists of a spinning disc component and a pivoting component. The spinning disc has a radius of 35mm to accommodate the area of the thumb. The surface of the discs have been sanded evenly with 80 grit sandpaper, as done in prior work[25]. A Dynamixel MX-12W servo motor ($32 \times 50 \times 40mm$, RPM: 470, Weight: 54.6g, Voltage: 12V, Signal latency: $\leq 0.5ms$) actuates disc spin. The disc can pivot in a range of 180°, and the pivoting is actuated by a Dynamixel XL-320 servo motor ($24 \times 36 \times 27mm$, RPM: 114, Weight: 16.7g, Voltage: 8.4V, Signal latency: $\leq 0.5ms$). To ensure the point of fingertip contact on the disc is relatively consistent and to prevent the fingertips from touching other moving parts, a 3D-printed finger guard (Figure 5) is placed above each disc module with an aperture of $25 \times 30mm$, the center being set at a 20mm distance from the spin axis of the disc.

The two disc modules are attached back to back on the handheld housing and slide along stainless steel rods via linear bearings. Two width-change actuators (Dynamixel XL-320) adjust the distance between the modules via rack & pinion gears in a range of $26-50mm$

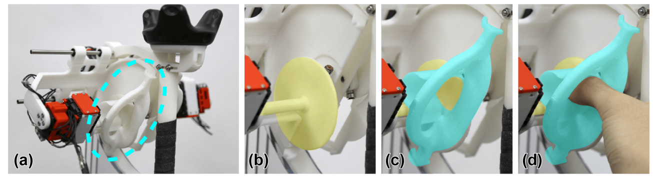

Figure 5: The finger guard. (a) placement of the finger guard in relation to the disc module; (b) spinning disc and axle exposed (highlighted in yellow); (c) the finger guard (highlighted in cyan) limits the area of spinning disc surface exposed to the user; (d) finger guard prevents user's fingertip from colliding with disc axle or slipping out of place while maintaining consistent area of fingertip contact.

(26mm is the minimum mechanically feasible, 50mm is from prior work[1]). The spinning pivoting disc modules are oriented 34° offset from the handle to prevent collisions with the rest of the hand due to pivoting, setting the pivoting range $34° - 214°$ degrees in relation to the handle.

All assembly components are 3D-printed in PolyLactic Acid (PLA). A 200g counter-weight is positioned below the handle to balance the center of mass when rotating *SpinOcchio* in various axes. The device dimensions are $340 \times 235 \times 275mm$, and weighs 883$g$.

The four XL-320 servo motors and two MX-12W servo motors are daisy-chained together by type, and each group is connected to the PC via serial communication with 1,000,000 bps baudrate through the Dynamixel U2D2 communication converter. The control firmware of the motors are based on the software development kit (SDK) provided by Dynamixel[1] and written in Python to run on a PC, and in C# to run within a VR environment created with Unity. The technical characteristics of *SpinOcchio* operation are described in the technical evaluation section below.

3.3 Technical Evaluation

We conducted a technical evaluation to determine *SpinOcchio*'s input-to-output latency, and mechanical reliability of output speed when a moderate load (e.g., grip force) is applied to the spinning disks.

3.3.1 Latency. The device has inherent latency due to limitation on the physical speed of the motors, processing time and of the communication link. We tested the maximum latency for each of the six motors in *SpinOcchio* — three motors for each side of the handle. These are the motors attached to the spinning and pivoting disks, and those attached to the width-changing pinion mechanism. To identify the maximum latency involved in reaching 90% (a method explored in [33]) of the desired target speed and position with unloaded motors, we developed a software in C# which would actuate each of the motors by outputting the minimum then the maximum speed (0 to 470 RPM) for the spinning disks, angles for the pivoting disks (0° to 180°), and widths of the grip (26 to 50 mm). We then read data from each motor in a closed-loop and computed

[1]https://emanual.robotis.com/docs/en/software/dynamixel/dynamixel_sdk/overview/

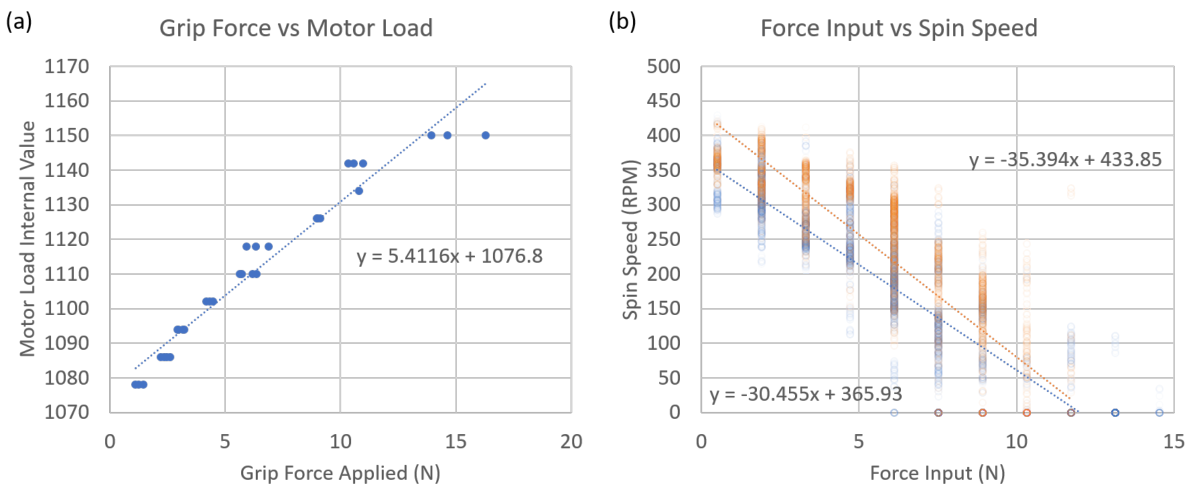

Figure 6: (a) User's grip force to width motor load conversion. The Y axis displays direct readings of internal Present Load values from the motor, as listed in the e-manual (https://emanual.robotis.com/docs/en/dxl/mx/mx-12w). (b) User's grip force to output spin speed.

the time necessary to reach the desired targets. Results, shown in Table 1, demonstrated that *SpinOcchio* can generate a skin-slip in any direction, of any intensity within the possible range, and with arbitrary grip size, with average motor response times ranging from 97 – 215 milliseconds (SD: 12 – 34ms), similar to prior work[25].

	Left			Right		
	Spin	Pivot	Width	Spin	Pivot	Width
Mean	102.4	203.5	96.6	97.7	215.9	108.2
SD	11.9	25.0	22.3	14.3	33.6	15.3

Table 1: Motor Latency Table (ms)

3.3.2 Effect of Grip Force on Spin Speed and Pivot Position. When users apply grip force on *SpinOcchio*, load-applied motors' behaviors may change. We tested the effect of grip force on spin speed and pivot position of the motors, divided into two parts. Because we cannot provide a consistent grip force while gripping and using the device, we first measured the load experienced by the width motor when an external force was applied. Then in the second part, we measured the width motor load, spin speed of the spinning motor, and the position of the pivot motor under varying grip forces. Using the grip-to-load relationship from the first part, we are able to interpret data from the second part.

To measure the load experienced by the width motors under varying grip forces, we used a push-pull force gauge (Nidec-Shimpo FGJN-5) to apply force onto the location where users' place the fingers. We then recorded the readings from the gauge and the internal load value of the motors. We applied increasing grip forces until no significant change in load value occurred (stopping at 16.3 Newtons), and the results are shown in Figure 6(a). A linear regression reveals strong linear relationship (R^2= 0.95) between the grip force and the motor load, with a load ceiling starting to occur at 14 Newtons.

To measure the spin speed under varying grip forces, we ran the motor at maximum speed of 470 RPM then applied increasing grip forces until the motor came to a stop. Using the motor's SDK, we read the load and the spin speed, collecting the data from five runs, each lasting twenty seconds or more. We then used the relationship established in the first part to convert and map out spin speed in relation to varying grip force, shown in Figure 6(b). At maximum spin rate, the motors' RPM drop linearly for every 1 Newton of force applied (left motor: 30 RPM, and right motor: 35 RPM). The results show that the motors stop when applied an average of roughly 12 Newtons of grip force (equivalent of the force needed to grip and hold a large soda bottle), suggesting a maximum grip force of 12 Newtons when using the device.

To measure the the pivot position under varying grip forces, we developed another software that output the pivot position going back and forth from minimum to maximum (0° to 180°). Again, using the motors' SDK, we then read the motor load and the pivot position, and found that the maximum deviation of pivot position was 4.4°.

4 STUDY 1 : ANGLE DISCRIMINATION THRESHOLD

To determine the perception discrimination threshold of skin-slip when tangential forces are applied on the fingertips, we conducted a study of Just-Noticeable Differences (JND) measuring humans ability to distinguish among relative changes of direction of tangential skin-slip forces. Compared to previous work [25] which studied JNDs for a single finger using a rolling sphere (i.e., single point of contact), we present a study that compares discrimination of one finger vs. two opposing fingers (e.g., grasp) with skin-slip rendered using a flat even surface (i.e., spinning disks).

4.1 Participants and Method

12 participants (six female, six male, with age 20 – 33, M:25.33, SD:4.75) were recruited for the study. All participants were right-handed and reported a normal sense of touch. Before the study, right hand index finger lengths were collected (M: 7.3cm, SD: 0.36cm) As compensation for their time, each participant received 10 USD in local currency.

The study closely follows the setup presented in previous work[25]. For each one of the two conditions (index vs. index+thumb), we employed a one-up two-down adaptive staircase method to determine the minimum angle (ΔS) when two tangential forces of equal intensity but different directions are applied. At each trial, participants were presented with three stimuli rendered in succession but in random order, among which two were the same (S) and one was the test stimulus ($S + \Delta S$). In accordance to a forced-choice paradigm[17], they were then asked to select the stimuli perceived different from the others.

Each stimulus involved the spinning disc in contact with the fingertips moving at $50mm/s$ [25] for a duration of $1s$ (RPM: 23.816). For the two-fingers condition the grip width was $50mm$ in accordance to previous work [1]. The reference angle of S was set to $0°$, representing tangential skin skip force pulling away from the user (applied in a distal direction along the longitudinal axis of the fingers). The test angle, instead, was set to be greater than the reference angle by ΔS, which at the start was set to $60°$ [25] to then be determined adaptively (i.e., it could grow or shrink). Again following prior work, each step was set to be $15°$ for the first three reversals, and decreased to $5°$ for the following 12 reversals [25]. The mean of the last 10 reversals was used to determine the JND value.

After 15 reversals, a staircase was complete, and following a brief break, the next staircase was conducted for the other finger-condition. Conditions were presented in balanced order, and took approximately 15 minutes to complete. The whole study (inclusive of demographics, debriefing, and break) took 45 minutes.

4.2 Study Setup

The study setup is illustrated in Figure 7. We used a monitor for displaying the instructions, a keyboard for response input (i.e., the three choices where mapped to the keys 1,2,3), and *SpinOcchio* firmly placed on laser-cut stand for rendering the stimuli. Initially (and at the beginning of each of the three studies), participants were given instructions on how to hold the device properly, to ensure that *SpinOcchio* was gripped evenly from both sides in case of using two fingers. Participants were shown and asked to place the thumb and index fingertips inside the finger guard first and then were asked to hold the handle with the remaining three fingers afterwards. At each trial, participants were instructed through a prompt on the monitor to place their fingertips on the discs with their dominant hand and to press the spacebar on the keyboard with the other hand to receive the tangential skin-slip stimulus. To block any visual or auditory cue from the motors, *SpinOcchio* was placed behind a barrier and participants wore headphones playing white-noise. To further prevent participants of educated guessing based on possible sound leaks, the disks of *SpinOcchio* were randomly oriented between stimuli.

Figure 7: The JND study setup. Participants listened to white-noise through headphones as they experienced skin-slip feedback with their dominant hand and input their response with their other hand through keyboard input.

4.3 Results

The mean discrimination thresholds for the index only condition was 43.79° (SD:18.54) and for index and thumb together condition was 66° (SD: 28.79) (Figure 8). Paired-samples t-test results ($\alpha = 0.05$) indicate that detection thresholds were statistically significantly lower in the index only condition compared to the index and thumb together condition ($t(11) = 3.141$, $p = 0.009$).

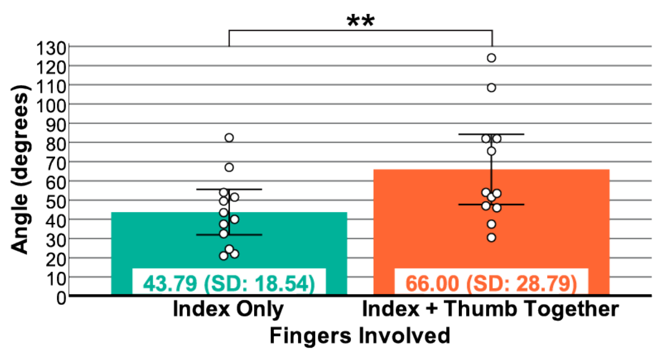

Figure 8: Mean angle discrimination thresholds of the JND study, for each finger combination. Error-bars represent 95% confidence intervals. Within in each column, each circle represents a different participant.

Two main findings emerged from the results. The first was, despite that the spatial accuracy differed between the two finger-conditions, the average total discrimination of skin-slip (54.90° SD: 25.70) is aligned with that reported in prior work (53.10°, SE: 5.05°, [25]). This suggests the feasibility of the pivoting spinning disc mechanism used in *SpinOcchio* for rendering skin-slip. The second finding is more surprising because it shows that a single finger (index) outperformed the spatial discrimination of two fingers simultaneously exposed to the same stimulus (index+thumb forming a grip). We speculate that this result is perhaps related to the *assimilation effect* [19], which explains why the perceived roughness of a surface scanned with the index finger can be altered by the stimulus presented on an adjacent finger. Although the full explanation of this finding is beyond the scope of this paper, it is clear that the stimulation of adjacent digits via spinning disks resulted in a stronger inhibitory interaction, as also seen in the literature [4].

Additionally, a Pearson product-moment correlation was run to determine the relationship between index finger length (hand size) and JND values. Although not statistically significant, there was a weak, negative correlation between index finger length and index-only JND ($r = -0.201$, $n = 12$, $p = 0.530$) and a weak, positive correlation between index finger length and JND of index and thumb together ($r = 0.396$, $n = 12$, $p = 0.202$). These results seem to indicate that there is no correlation between participant hand size and skin-slip direction perception sensitivity while using *SpinOcchio*.

Considering the limited hand size range and sample size surveyed in the study, however, further research with a larger participant pool consisting of a broad range of hand sizes would be necessary to draw strong conclusions about the relationship between hand size and skin-slip direction perception.

5 STUDY 2: HAPTIC-VISUAL CONGRUENCE

Building upon our understanding of the discrimination threshold of skin-slip on the fingertips and prior work demonstrating better texture discrimination in certain directions during passive over active touch [23], we designed a second user study to further explore how the haptic perception may be affected by the presence of visual and cutaneous proprioceptive cues. Specifically, we aim to understand the *haptic-visual congruence* [32] of skin-slip stimuli rendered by *SpinOcchio* in the presence of VR visuals (moving objects of different shapes), and in relation to the user's hand movements.

Here are the independent variables explicitly considered in the study (see Figure 9 and Figure 10):

1. Hand Movement

Closely related previous work [25, 39] studied skin deformations resulting from the users' direct movement of their hands (Figure 9-left). In this study, we presented to the participants virtual objects that they experienced by actively moving their hand along the length of the object (*Active* condition) vs. objects that moved while the participants' hands remained fixed (*Passive* condition). The *Passive* condition provides a baseline for our analysis.

In the *Active* condition the direction and type of motion were constrained (i.e., vertical/horizontal, translational/rotational), such that any movements not congruent with the direction of motion were ignored. The speed and the length of movements were up to the users. In the *Passive* condition all participants experienced the same amount of displacement ($200mm$, moving back and forth, 4 seconds in each direction) with the same speed ($50mm/s$), for each type of motion. Specifically, motions were presented in the order forward/downward followed by backward/upward for translations, and clockwise and anticlockwise for rotations.

2. Virtual Objects

To test the effect of different types of motions (translation/rotation) we selected two different virtual objects (a cuboid and a cylinder) in two orientations (vertical and horizontal), for a total of four different virtual object conditions: *Vertical Cuboid*, *Horizontal Cuboid*, *Vertical Cylinder*, and *Horizontal Cylinder* (Figure 9-right). These objects were chosen not only because they afford two types of motions (translation/rotation) but also because they result in different skin-slip feedback: translation applies skin-slip in the same direction for both fingertips while rotation does in opposite directions.

In practice, all virtually oriented objects had a dimension of $300 \times 50 \times 50mm$, rendering a grip width of $50mm$, consistent with Study 1. To ensure that object motion, especially rotation, was visually perceived correctly, all objects had a VR visual texture pattern similar to that used in past work[14].

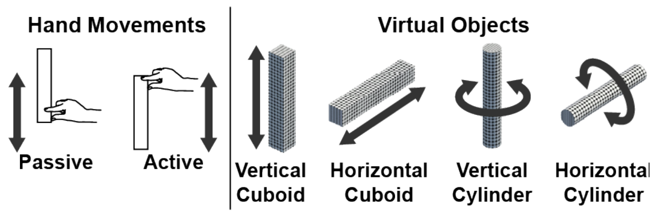

Figure 9: *Hand Movement* and *Virtual Object* variables of Study 2.

3. Haptic Direction Mapping

Inspired by prior work which found that one-dimensional haptic stimulus was perceived realistic even if incongruent with visuals [39], in this study, we borrow the same technique to investigate the congruence of various skin-slip mapping with visual 3D objects. Therefore, we created four different mappings: 1) *Congruent* involves skin-slip in the same direction as the object's motion; 2) *Reverse* presents haptic cues in the opposite direction of how motion is visually perceived; 3) *Pitch(+90)* and 4) *Pitch(-90)* present haptic cues that are orthogonal (on the positive or negative axes) to the direction of how motion is seen. To these four mappings, we also added a no-haptic condition to provide a baseline.

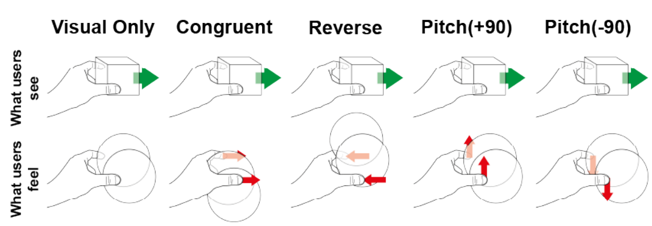

Figure 10: Example conditions of the *Haptic Direction Mapping* variable of Study 2 applied to a virtual cube object moving forward. Top row represent motion of the virtual object. Bottom row represents corresponding skin-slip direction per condition.

To further clarify these haptic mappings with an example (Figure 10), consider the case of a *Horizontal Cuboid* object which moves between the fingers of a *Passive*, non-moving hand. The skin-slip rendered on the fingertip is *Congruent* if a forward translation causes the skin to move along the same direction, *Opposite* if a forward movement displaces the skin toward the user, *Pitch(+90)* if a forward movement causes the skin to be dragged upward, and *Pitch(-90)* if the forward movement causes the skin to be dragged downward. The no haptic condition would result in a visual stimulus alone.

5.1 Participants and Method

12 participants (eleven male, one female, with age 19-28, M:22.92, SD:3.37) were recruited for the study. All participants were right-handed and reported a normal sense of touch. As compensation for participation, each participant received $10 (USD) in local currency.

The study followed a $2 \times 5 \times 4$ within-subject repeated measures factorial design with two hand movements, five haptic direction mappings, and four virtual objects. The study was evenly balanced for *Passive* and *Active* hand movements, forming two blocks. For each block, the participants experienced five sets made of 20 randomized combinations of four objects × five haptic mappings, for a total of 100 trials per block. Each trial had a duration of 8 seconds.

For each trial, we documented perceived realism on a 7-point Likert scale (1-Strongly Disagree, 7-Strongly Agree with the prompt "The haptic rendering matched my visual impression of the scene") as in [39]. The scale and prompt closely followed those of the prior work for consistency. We do, however, recognize that they are not of a standardized scale. We also recorded the raw position and orientation of the controller in space, and, at the conclusion of each block, we collected the perceived workload using the NASA TLX[13].

5.2 Study procedure and Setup

After collecting demographics and debriefing, participants remained seated and were asked to wear a HTC VIVE head-mounted-display (HMD) and to calibrate the HMD to match the distance between their eyes for clear vision in VR. They were instructed to hold the haptic device with their dominant hand the VIVE controller in the other, to be used as the input device. In the *Passive* block the device remained stationary and the participants' hands rested on a stand, while in the *Active* block users could move the device and rest it on their laps between trials. Participants also wore noise-reducing earmuffs over their ears to reduce ambient noise and sound from *SpinOcchio*'s motors.

The *SpinOcchio* controller was tracked in 6DOF using a VIVE tracker, and, as in [7], the fingers in contact with the device were rendered as two gray capsules. Furthermore, following the recommendation of a reduced visual-to-haptic feedback ratio for achieving higher discrimination thresholds and lower discomfort for skin-slip [25], haptic translation/rotations were mapped to a reduction of 60% from their corresponding visual feedback. For example, a $50mm/s$ visual stimulus corresponded to a $20mm/s$ haptic stimulus (as in [25]).

Upon entering the VR study scene, participants first pulled the trigger on the controller while holding *SpinOcchio* to start a trial. After exploring the object for eight seconds they were prompted to rate the experience on a Likert-scale, as described above, the congruence of the visuo-haptic experience. Participants were also instructed to lift their fingertips off the disks after experiencing each trial, while the disks randomly moved to mask any auditory cue and then repositioned for the next trial. The experiment lasted 60 minutes and participants could ask for a break or to interrupt the study at any time.

5.3 Results

The results were analyzed using repeated-measures ANOVA followed by pairwise comparisons with Bonferroni correction ($\alpha = 0.05$). Mauchly's Test of Sphericity was conducted, which indicated that the assumption of sphericity had been violated ($\chi^2(5) = 18.634$, p = 0.002), and therefore, a Greenhouse-Geisser correction was used.

Results indicated a main effect of *Haptic Mapping* (F(2.144, 23.588) = 84.859, p < 0.0005, ${\eta_p}^2 = 0.885$) and *Virtual Object* (F(1.473, 16.198) = 8.067, p = 0.006, ${\eta_p}^2 = 0.423$) on participant's congruence agreement scores. There was no indication of main effect of *Hand Movement* (F(1.000, 11.000) = 0.524, p = 0.484, ${\eta_p}^2 = 0.045$), but we report an interaction effect present between *Hand Movement* and *Haptic Mapping* (F(2.868, 31.547) = 5.618, p = 0.004, ${\eta_p}^2$=0.338), *Hand Movement* and *Virtual Object* (F(2.047, 22.515) = 4.797, p = 0.018, ${\eta_p}^2$ = 0.304), and between *Haptic Mapping* and *Virtual Object* (F(3.434, 37.778 = 4.557, p = 0.006, ${\eta_p}^2$ = 0.293).

Pairwise comparisons revealed that, for *Haptic Mapping*, the *Visual Only* condition was strongly significantly different from all the haptic conditions (p < 0.001). Among the *Virtual Objects*, we report a significant difference between the *Vertical Cuboid* and the *Vertical Cylinder* conditions (p = 0.018), and between the *Vertical Cylinder* and *Horizontal Cylinder* conditions (p=0.029), as in Figure 12. Finally, we also note significant differences due to the interaction of *Hand Movement* (proprioceptive condition) and *Haptic Mapping*. As visible in Figure 11, we found, in fact, a significant difference between the *Congruent* and the *Pitch(+90)* mappings (p = 0.029) when hand movement was *Passive*, and that, by switching the order of comparison, differences occurred between the *Active* and *Passive* hand movements only for the *Congruent* mapping (p = 0.027).

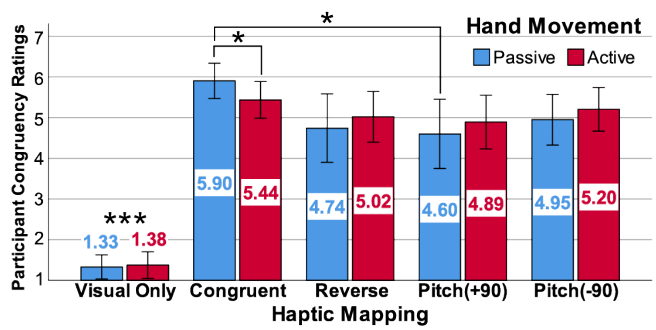

Figure 11: Mean participant ratings for each *Haptic Direction Mapping* condition, per *Hand Movement*. Error bars represent 95% confidence intervals.

To further understand how participants explored the virtual objects in the *Active* condition, we also analyzed the raw data from the trackers and derived the velocity and angular velocity associated to translations and rotations of the *SpinOcchio* controller. We ran a Spearman's correlation test between speed and the self-reported

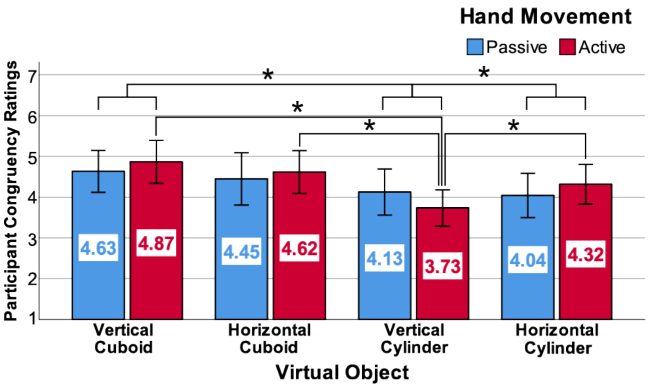

Figure 12: Mean participant ratings for each *Virtual Object* condition, per *Hand Movement*. Error bars represent 95% confidence intervals.

congruence rating scores above (*Congruence Rating*), which revealed a weak, positive correlation between the *Congruence Rating* and *Velocity* (r_s = 0.244, p < 0.0005), and a weak, negative correlation between *Congruence Rating* and *Angular Velocity* (r_s = -.230, p < 0.0005).

A paired-Samples t-test (α = 0.05) on the TLX overall workload revealed a significant difference between hand movement conditions (t(11) = -3.230, p = 0.008). Of the task load factors, *Physical Demand* scored higher for *Active* (t(11) = -6.824, p < 0.0005), probably due to the effort of lifting and moving the device. TLX score results of participants are shown in Figure 13.

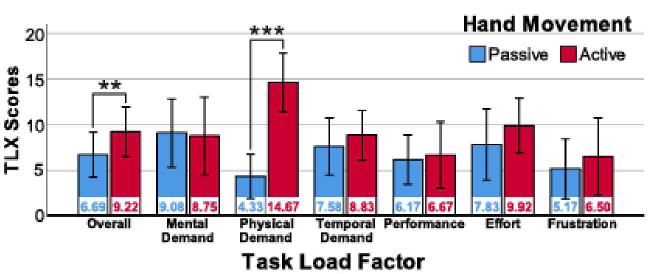

Figure 13: TLX scores per task load factor, for each Hand Movement condition. Error bars represent 95% confidence intervals.

5.4 Discussion

These results, combined with those from the JND study, describe a simple yet interesting result. First of all and not surprisingly, all *Haptic Mapping* conditions with any haptic feedback were perceived as more congruent than the visual-alone modality (1.36 vs. 5.09), regardless of the type of *Virtual Object* explored and *Hand Movement* involved. This indicates that the rendered skin-slip feedback was well perceived by the participants and that it was convincingly congruent with the visuals provided. However, despite the *Congruent* mapping for both *Hand Movement* conditions having the highest mean congruency ratings, almost no significant difference was observed among the haptic conditions. In fact, it appears that in most cases, haptic feedback, congruent or incongruent, in presence of visual cues, was perceived as similar in congruence with the visuals. Although it is difficult to conclude that there is a significant difference between different haptic mappings that affects congruency perception, considering the limited sample size, more power (and a power analysis) would be required to conclude that there is in fact no difference between the haptic mappings affecting congruency perception. Nevertheless, it seems that in the presence of visual cues, it is difficult to discern the congruency of haptic feedback to the visuals.

This is quite an interesting result if we consider that the JND discrimination (43.79°) is significantly below the ±90° of the *Pitch* mappings and the 180° of the *Reverse* mapping. In other words, participants surprisingly interpreted as "coherent with visuals" even the Reverse and Pitch mappings, while in the JND study with the same setup they were capable of a finer level of discrimination. Therefore, the lack of significant differences between haptic stimuli cannot be explained in terms of haptic perception alone, nor can be attributed to hardware limitations, but it must be related to the presence of the visual stimuli. We believe that, as in prior work, which demonstrated that for 1-dimensional movement direction of skin-slip in the reverse direction of motion was still perceived as realistic [39], in this work also, the visual modality dominated over the haptic modality. Finally, it is worth noting that in the case of *Passive* hand movements, the participant ratings significantly differed between the *Congruent* and the *Pitch(+90)* mappings and that for the *Congruent* mapping, ratings significantly differed by *Hand Movement*. These suggest that some level of proprioception due to the hand motion is also involved in congruency perception (i.e., when no hand movement is required, it might be easier to differentiate incongruent directions). Again, due to the limited study sample size, further investigation with a larger sample size is required to draw stronger conclusions and verify whether *Reverse* or *Pitch(-90)* mappings can indeed be discriminated from *Congruent* mapping when no hand motion is involved or whether *Congruent* mapping is significantly better than any other mapping.

In summary, these study results strongly suggest that the participants perceived higher sensory congruence for the combined haptic+visual modalities compared to the visual modality alone, but that, at the same time, the visual-haptic congruence was strongly affected by the presence of visual cues.

6 STUDY 3: VR REALISM

While in our previous studies we focused on the skin-slip perception and the visuo-haptic congruence by applying constraints on how the *SpinOcchio* controlled could be moved, in this study we aim to explore the perceived realism, enjoyment and immersion of a VR experience with *SpinOcchio*, where the users can freely move the controller. Furthermore, we also introduce the width-changing feature of *SpinOcchio*, which allows the user to perceive skin-slip for objects of nonuniform shapes by increasing or decreasing the distances between the gripped spinning disks.

6.1 Participants Method and Study Setup

12 volunteers (seven female, 5 male, aged 20-33, M:25.17, SD:4.53) were recruited for the study. All participants were right-handed

and reported a normal sense of touch, and were compensated with 10 USD in local currency.

The study follows a within-subjects repeated measure design with *Varying Width* as independent variables presented in balanced order. The width was *Static* if it did not change, like in the previous studies ($26mm$), or *Dynamic* if it varied according to the visual stimuli ($26 - 50mm$).

For each of the width conditions, participants were allowed to freely explore a VR space with various objects (like in Figure 14), clustered in three groups: static objects, objects moving on a single axis (e.g., translation or spinning), and objects moving on two axis (e.g., translation and simultaneously spinning). The virtual objects (discs and beams) were also constructed with profiles of varying width, following a sinusoidal pattern. Textures were applied for visual clarity as in the previous study. In this scene, users were free to touch and explore any of the objects for as long as they wanted and in the desired order. We only request them to spend at least 5 minutes total and to touch each of the 18 objects in the virtual room.

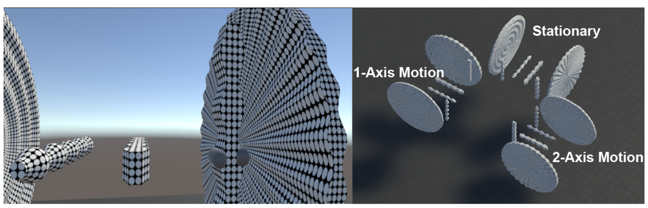

Figure 14: VR scene of Study 3. Left: Participant's point of view. Gray capsules represent both fingertips. Right: Overhead view of scene layout of virtual objects groups to be explored in the scene.

The experiment followed a very similar procedure as that described in the congruence study, and the *SpinOcchio* apparatus and its configuration were also the same. After debriefing, participants were instructed to wear the VIVE HMD. Then they completed each of the two modality sessions (*Static* vs. *Dynamic* width), each followed by a questionnaire and a break. Finally a post-hoc interview inquiring about the perceived differences. Including the final interview, the study duration took approximately 40 minutes to complete.

For the analysis we collected two types of data. Following prior work [25, 33, 36], we collected 7-point Likert scale ratings (1-strongly disagree, 7-strongly agree) on VR experience evaluation criteria, specifically for realism, enjoyment and immersion. The questionnaire prompt for realism and immersion were written out into question format, adapting from the iGroup Presence Questionnaire (IPQ)[2] Realism Question#2 and IPQ Involvement Question#1, respectively: Realism - "Compared to when touching an object in reality, I felt that the visual-haptic experience was realistic"; Immersion - "I felt that I was completely immersed by the visual-haptic experience and forgot about reality"; Enjoyment - "I felt that the visual-haptic experience was enjoyable." Participants were given verbal instructions and translation in local language as necessary, as well as clarifications of jargon by the same researcher; specifically, "visual-haptic experience" was explained as the "combined experience of what you see in VR and what you feel on your fingertips". We also collected a first-person view video footage of how participants interacted with each object, allowing to determine how many times objects were touched and for how long.

[2]http://www.igroup.org/pq/ipq/index.php

6.2 Results

A related-samples Wilcoxon signed rank test ($\alpha = 0.05$) revealed that between the two width conditions, there was no significant difference in perceived realism (Z < 0.0005, p=1.000), enjoyment (Z = -0.816, p = 0.414), or immersion (Z = -0.276, p=0.783). Mean participant ratings are shown in Figure 15.

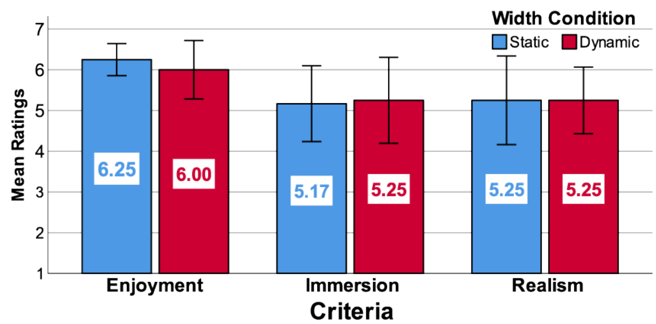

Figure 15: Mean participant ratings for each evaluation criterion, per *Width* condition. Error bars represent 95% confidence intervals.

The time (Figure 16) participants spent per each set of objects was extracted from the video recordings. Participants spent on average 224.67 seconds (SD: 61.67) on the 1-axis movement set, 138.17 seconds (SD: 40.65) on the stationary set, and 225.92 seconds (SD: 60.357) on the 2-axis movement set during the duration of the study. A two-way ANOVA ($\alpha = 0.05$) revealed that participants spent significantly different amount of time based on the type of *Object Motion* ($F(2, 66) = 10.691$, $p < 0.0005$, $\eta_p{}^2 = 0.245$), with *Stationary* objects (i.e., the participants had to actively move their hand) the least preferred (69 seconds on average spent for the Stationary set). This was corroborated in the post-hoc interview, where the participants described to prefer the sets where object moved on their own (e.g., "I can focus on the perception" (P1) and it was "more fun" (P6, P7)). On the other hand, no time differences emerged between the grip conditions (Static vs. Dynamic grip).

Finally we analyzed the interview quotes, and report here some highlights. When asked to describe the difference perceived when comparing the two width conditions, only one out of twelve participants (P9) indicated that they did not feel width change in the passive condition. All other participants indicated perceiving a change in "intensity," between the two conditions but not the absence of width change in one over the other condition. The feedback is best described in the words of the participants: P11 said "it (dynamic width) felt more exaggerated than the first session (static width)." P8 said that during static width, they "felt very little physical width change" and that the "(feedback) amplitude was not high." P12 said, "Both sessions were very similar in surface and width feedback.

Because I did feel width change in both sessions, I thought there was no difference (between the two conditions)."

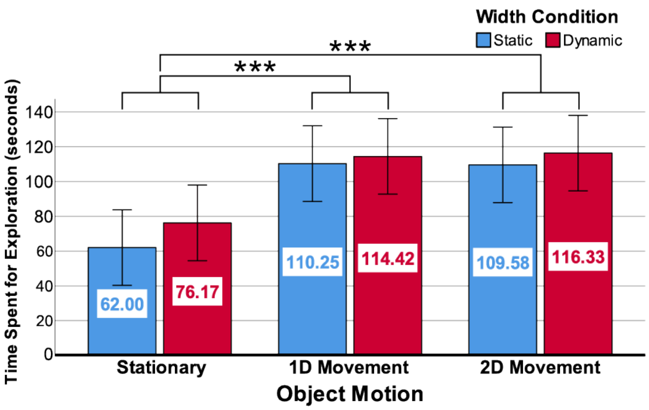

Figure 16: Mean time spent by participant for each *Object Motion Type*, per *Width* condition. Error bars represent 95% confidence intervals.

6.3 Discussion

Two main findings emerged from Study 3. The first is that all participants consistently rated relatively high Enjoyment (M: 6.125) and moderately high Immersion (M: 5.21) and Realism (M: 5.25) for both dynamic and static grip conditions. The fact that realism was perceived high was unsurprising, as already partially shown in Study 2 and previous related work [25, 26, 39]. The second, and more important finding, is that no significant differences were observed between the *Static* and *Dynamic* grip width conditions, suggesting that the dynamic width change may have had little impact on the user enjoyment, perceived immersion and realism. In other words, the visual feedback appeared to dominate also over the kinesthetic haptic feedback (normal forces). This result indeed aligns with prior work[5], which showed evidence of cross-modal sensory illusion with participants reporting haptic sensations of "physical resistance" even if no haptic display was present. In summary and combining the results from our studies, we can conclude that in the presence of visual cues, *both* the tactile (skin-slip) and kinesthetic (normal forces) haptic feedback are strongly affected by the visual modality. However, considering the study is underpowered due to limited sample size, further investigation with a larger sample size with an accompanying power analysis would be required to provide sufficient evidence to claim whether there is a difference caused by *Width condition*.

7 APPLICATIONS

SpinOcchio can simulate the sensation of virtual objects of varying thickness slipping between the fingertips at different speeds in different directions. To demonstrate the range of interactions with objects in VR enabled through *SpinOcchio*, we present three demo applications that best showcase the strengths of the device.

7.1 Structural Manipulation

SpinOcchio can express the width of virtual objects by adjusting the grip width and the objects' movement speeds and directions through the disk spin and pivot, respectively. With the addition of grip-sensing capability enabled by reading via the SDK the load applied to the width motors, the device can function as a simultaneous input-output device that changes width in response to applied grip force. Such response to grip force enables users to manipulate moving virtual objects in real-time through squeezing.

In the Potter's Wheel application (Figure 17), users can not only feel the contours of the spinning clay, but they can also directly mold the clay simultaneously by squeezing their grip. As the clay deforms, users are able to perceive the slower surface movement of the clay at regions with smaller diameters compared to the speed at other regions with larger diameters.

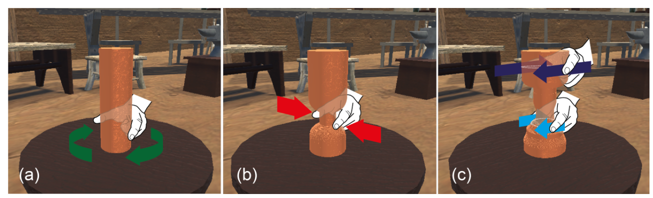

Figure 17: The Potter's Wheel application. (a) Motion of rotating clay felt by touching. (b) Squeezing the clay reduces its diameter (c) Different parts of the clay with different widths can felt as well as different skin-slip speeds.

7.2 Gripping & Slipping of Rigid Objects

By varying the speed of disk spin speed relative to hand movement, *SpinOcchio* can express the movement of rigid objects held in the hand. Through sensing grip-force, the disk spin speed can be adjusted in response to the grip force applied. The speed change in response to grip force can enable users to grab, pull, or release objects in VR.

In the Weight and Pulley application (Figure 18), users can move their hand up and down to feel the rope between their fingertips. By squeezing the grip, users can hold the rope, and when the user moves their hand, the rope follows the hand while no skin-slip is applied on the fingertips. Pulling the rope lifts the weight on the other end of the pulley off the ground. After lifting the weight, users can un-squeeze their grip to release the rope they were holding and feel the skin-slip as the rope slips between their fingertips as the weight falls back to the ground. By varying how hard they squeeze the grip, users can control the speed at which the rope slips between their fingertips.

7.3 Material Characteristics

Through varying both disk rotation amount and grip width in response to relative hand movement, *SpinOcchio* can express material properties of virtual objects held in the hand. The grip width and skin-slip distance change in response to hand movement enables users to feel, pull, and stretch objects of different elasticity in VR.

In the Material Laboratory application (Figure 19), users can feel materials of different elastic properties as they move their

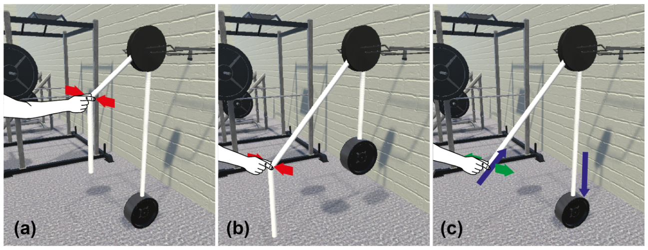

Figure 18: The Weight and Pulley application. (a) Rope can be squeezed to be held in the hand. (b) Pulling the rope while squeezing lifts weight off the ground. (c) Right: Releasing the squeezing makes rope slip between fingers and weight falls to the ground.

hands up and down the samples. When touching a stiff sample, the skin-slip distance (L_s) applied to the fingertips is equivalent to the hand movement distance (L_a). However, for elastic objects, the experienced skin-slip distance (L_s) is shorter than hand movement distance (L_a), reflecting the phenomenon perceived when pulling on elastic material. To render this phenomenon with SpinOcchio in terms of disk speed, the speed of the disks can be set to be proportional to the ratio between (L_s) and (L_a).

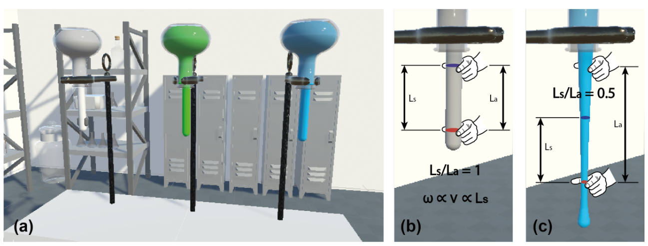

Figure 19: The Material Laboratory application. (a) Different material samples available for interaction. (b) Visual to skin-slip distance ratio for stiff material. (c) Visual to skin-slip distance ratio for elastic material.

8 DISCUSSION & LIMITATIONS

In this paper, we proposed a novel haptic controller named *SpinOcchio*, which operates based on spinning and pivoting disks, capable of rendering the sensation of skin-slip — the cutaneous stimulation generated by two fingers gripping an object when sliding over its profile. Through our studies, we were able to determine the baseline haptic discrimination threshold and confirmed that the threshold with two fingers is comparable with that for a single finger reported in prior work[25]. We also explored how the haptic realism of motion and thickness is perceived with congruent and incongruent visual stimuli, finding that the participants perceived the VR experiences to be more realistic when the visuals were combined to any of the haptic directional mappings, rather than when they were presented alone. We also found that, similarly to previous work [5], when skin-slip was combined with a visual of a deforming grip (i.e., sliding the fingers over an object of varying width), participants were not able to distinguish cases when the forces were really applied (i.e., the grip really changed in width) from cases in which the grip width only changed visually.

These results combined show once again [39], but this time for gripping fingers, that when skin-slip and normal forces are supplemented by visual cues, the visual modality dominate. These results, not only further deepen our understanding of haptic perception and skin-slip, but also support the development of possible applications that could leverage haptic illusions [24]. As, for example, the authors of the *Haptic Revolver* understood that to realistically render the feedback of a finger sliding over a surface the direction of motion of the surface textures is irrelevant [39], so could we envision applications that would similarly employ this trick in 3D — the cutaneous sensation of rolling a ball in the hand could be rendered without the need to physically reproduce the underlying forces.

Our work, however, also has limitations and presents opportunities for improvement. Several limitations stem from the physical form factor of the hardware. The necessity of using large spinning disks r = 40 mm that allow a user to comfortably and reliably place the finger near the edge, required to limit pivoting from 0° to 180°, as described in the System Description section. The consequences of these choices are a handle positioned 60 mm away from the spinning disks, making it difficult for people with small hands to use our device. The resulting size of the device also contributed to a larger weight and possibly to a higher latency than a more compact system. The flatness of the disks makes it challenging to render curved surfaces and edges.

Hardware usability issues of large grip size, bulkiness, and weight can be addressed through the following approaches: Firstly, the handle of *SpinOcchio* at a fixed distance from the finger guard prevents users with short fingers from reaching the spinning discs at all. Aside from marginally reducing the distance by shrinking handle girth, more effectively, the device may be grounded on the user's hand or arm, in a wearable form factor, thus removing the need for a handle and freeing the user's hand. Secondly, as the bulkiness of the hardware is from the combination of mechanisms enabling 6-DoF skin-slip, in case investigation with larger sample sizes confirms that skin-slip direction or grip width is not discriminable when using *SpinOcchio* in VR, the degrees of freedom of skin-slip can be reduced, which in turn reduces device complexity and volume. Additionally, smaller actuators such as micro gearmotors can be used instead of servos to further decrease the volume and weight of the device as well, allowing for highly flexible skin-slip interactions in the hand.

Study limitations regarding sample size, reliability of measures, and appropriateness of study tasks should be considered when interpreting study results. With sample sizes limited and the studies underpowered, future work with larger sample size with follow-up power analyses would allow for drawing strong conclusions. Also, although the measures employed in studies 2 and 3 follow prior works [33, 39], they have not been evaluated for validity and reliability. Future work using standardized measures can validate the results found. Additionally, although the tasks used in studies 2 and 3 were adapted from prior works [7, 39], they may not be the most representative of every-day skin-slip perception tasks. Further investigation of the appropriateness of employed tasks may reveal which interactions may be more appropriate for applying haptic feedback with *SpinOcchio*.

In our first two studies, skin-slip speed ratios were fixed and chosen from prior work [25] which already explored different options. Future work might look into the effect of speed also for two fingers skin-slip. Furthermore, again following prior work [25, 39], we did not use a real-time position control closed-loop but opted instead for a speed-control loop. Although in practice we did not see participants attempting to stall the motors by gripping the disks with high forces, future work could improve this technical aspect, allowing for just skin stretch without movement. Finally, we only demonstrated a small set of applications. Future work can expand on these, touching domains such as remote telepresence, bimanual interactions where the user could grip and manipulate virtual objects with two hands, medical training (e.g., simulate the act of palpation), gaming and simulations — ultimately contributing to create more realistic VR experiences and perhaps bringing a positive spin to haptics.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2020R1A2C1012233).

REFERENCES

[1] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D Wilson. 2016. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 chi conference on human factors in computing systems*. 1968–1979.

[2] Joshua H Bacon and Linda Shaw. 1982. Effect of conflict awareness on visual dominance. *Perceptual and motor skills* 54, 1 (1982), 263–267.

[3] 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*. 717–728.

[4] Katja Biermann, Frank Schmitz, Otto W Witte, Jürgen Konczak, Hans-Joachim Freund, and Alfons Schnitzler. 1998. Interaction of finger representation in the human first somatosensory cortex: a neuromagnetic study. *Neuroscience letters* 251, 1 (1998), 13–16.

[5] Frank Biocca, Jin Kim, and Yung Choi. 2001. Visual touch in virtual environments: An exploratory study of presence, multimodal interfaces, and cross-modal sensory illusions. *Presence: Teleoperators & Virtual Environments* 10, 3 (2001), 247–265.

[6] Daniel KY Chen, Jean-Baptiste Chossat, and Peter B Shull. 2019. Haptivec: Presenting haptic feedback vectors in handheld controllers using embedded tactile pin arrays. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–11.

[7] 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*. 119–130.

[8] 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 *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 986–993.

[9] 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*. 1–13.

[10] Massimiliano Di Luca and Arash Mahnan. 2019. Perceptual limits of visual-haptic simultaneity in virtual reality interactions. In *2019 IEEE World Haptics Conference (WHC)*. IEEE, 67–72.

[11] Marc O Ernst and Martin S Banks. 2002. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature* 415, 6870 (2002), 429–433.

[12] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. 2020. Wireality: Enabling complex tangible geometries in virtual reality with worn multi-string haptics. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–10.

[13] Sandra G Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology*. Vol. 52. Elsevier, 139–183.

[14] Seongkook Heo, Jaeyeon Lee, and Daniel Wigdor. 2019. PseudoBend: Producing haptic illusions of stretching, bending, and twisting using grain vibrations. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 803–813.

[15] James M Hillis, Marc O Ernst, Martin S Banks, and Michael S Landy. 2002. Combining sensory information: mandatory fusion within, but not between, senses. *Science* 298, 5598 (2002), 1627–1630.

[16] 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 *2015 IEEE World Haptics Conference (WHC)*. IEEE, 189–195.

[17] Lynette A Jones and Hong Z Tan. 2012. Application of psychophysical techniques to haptic research. *IEEE transactions on haptics* 6, 3 (2012), 268–284.

[18] Amanda L Kaas, Hanneke I van Mier, Johan Lataster, Mirella Fingal, and Alexander T Sack. 2007. The effect of visuo-haptic congruency on haptic spatial matching. *Experimental brain research* 183, 1 (2007), 75–85.

[19] Mirela Kahrimanovic, Wouter M Bergmann Tiest, and Astrid ML Kappers. 2009. Context effects in haptic perception of roughness. *Experimental brain research* 194, 2 (2009), 287–297.

[20] Tanja Kassuba, Corinna Klinge, Cordula Hölig, Brigitte Röder, and Hartwig R Siebner. 2013. Vision holds a greater share in visuo-haptic object recognition than touch. *Neuroimage* 65 (2013), 59–68.

[21] Hwan Kim, HyeonBeom Yi, Hyein Lee, and Woohun Lee. 2018. Hapcube: A wearable tactile device to provide tangential and normal pseudo-force feedback on a fingertip. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–13.

[22] Robert Kovacs, Eyal Ofek, Mar Gonzalez Franco, Alexa Fay Siu, Sebastian Marwecki, Christian Holz, and Mike Sinclair. 2020. Haptic pivot: On-demand handhelds in vr. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. 1046–1059.

[23] Susan J Lederman. 1981. The perception of surface roughness by active and passive touch. *Bulletin of the Psychonomic Society* 18, 5 (1981), 253–255.

[24] Susan J Lederman and Lynette A Jones. 2011. Tactile and haptic illusions. *IEEE Transactions on Haptics* 4, 4 (2011), 273–294.

[25] Jo-Yu Lo, Da-Yuan Huang, Chen-Kuo Sun, Chu-En Hou, and Bing-Yu Chen. 2018. RollingStone: Using single slip taxel for enhancing active finger exploration with a virtual reality controller. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. 839–851.

[26] Victor Rodrigo Mercado, Maud Marchal, and Anatole Lécuyer. 2019. Entropia: towards infinite surface haptic displays in virtual reality using encountered-type rotating props. *IEEE transactions on visualization and computer graphics* (2019).

[27] Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. 2007. Gravity grabber: wearable haptic display to present virtual mass sensation. In *ACM SIGGRAPH 2007 emerging technologies*. 8–es.

[28] Roderick P Power. 1980. The dominance of touch by vision: Sometimes incomplete. *Perception* 9, 4 (1980), 457–466.

[29] Roderick P Power and Anne Graham. 1976. Dominance of touch by vision: generalization of the hypothesis to a tactually experienced population. *Perception* 5, 2 (1976), 161–166.

[30] William Provancher. 2014. Creating greater VR immersion by emulating force feedback with ungrounded tactile feedback. *IQT Quarterly* 6, 2 (2014), 18–21.

[31] 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.

[32] Irvin Rock and Jack Victor. 1964. Vision and touch: An experimentally created conflict between the two senses. *Science* (1964), 594–596.

[33] Neung Ryu, Hye-Young Jo, Michel Pahud, Mike Sinclair, and Andrea Bianchi. 2021. GamesBond: Bimanual Haptic Illusion of Physically Connected Objects for Immersive VR Using Grip Deformation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–10.

[34] Ali Sengül, Michiel van Elk, Olaf Blanke, and Hannes Bleuler. 2018. Congruent visuo-tactile feedback facilitates the extension of peripersonal space. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 673–684.

[35] Mike Sinclair, Eyal Ofek, Mar Gonzalez-Franco, and Christian Holz. 2019. Capstancrunch: A haptic vr controller with user-supplied force feedback. In *Proceedings of the 32nd annual ACM symposium on user interface software and technology*. 815–829.

[36] Hsin-Ruey Tsai, Ching-Wen Hung, Tzu-Chun Wu, and Bing-Yu Chen. 2020. Elastoscillation: 3d multilevel force feedback for damped oscillation on vr controllers. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[37] Chi Wang, Da-Yuan Huang, Shuo-wen Hsu, Chu-En Hou, Yeu-Luen Chiu, Ruei-Che Chang, Jo-Yu Lo, and Bing-Yu Chen. 2019. Masque: Exploring lateral skin stretch feedback on the face with head-mounted displays. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. 439–451.

[38] Chi Wang, Da-Yuan Huang, Shuo-Wen Hsu, Cheng-Lung Lin, Yeu-Luen Chiu, Chu-En Hou, and Bing-Yu Chen. 2020. Gaiters: exploring skin stretch feedback on legs for enhancing virtual reality experiences. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–14.

[39] 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*. 1–12.

[40] Shunki Yamashita, Ryota Ishida, Arihide Takahashi, Hsueh-Han Wu, Hironori Mitake, and Shoichi Hasegawa. 2018. Gum-gum shooting: Inducing a sense of arm elongation via forearm skin-stretch and the change in the center of gravity. In *ACM SIGGRAPH 2018 Emerging Technologies*. 1–2.

[41] Vibol Yem, Mai Shibahara, Katsunari Sato, and Hiroyuki Kajimoto. 2016. Expression of 2DOF fingertip traction with 1DOF lateral skin stretch. In *International AsiaHaptics conference*. Springer, 21–25.

[42] Shigeo Yoshida, Yuqian Sun, and Hideaki Kuzuoka. 2020. Pocopo: Handheld pin-based shape display for haptic rendering in virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13.