HairTouch: Providing Stiffness, Roughness and Surface Height Differences Using Reconfigurable Brush Hairs on a VR Controller

Chi-Jung Lee
National Taiwan University
cjlisalee@cmlab.csie.ntu.edu.tw

Hsin-Ruey Tsai
National Chengchi University
hsnuhrt@gmail.com

Bing-Yu Chen
National Taiwan University
robin@ntu.edu.tw

ABSTRACT

Tactile feedback is widely used to enhance realism in virtual reality (VR). When touching virtual objects, stiffness and roughness are common and obvious factors perceived by the users. Furthermore, when touching a surface with complicated surface structure, differences from not only stiffness and roughness but also surface height are crucial. To integrate these factors, we propose a pin-based handheld device, HairTouch, to provide stiffness differences, roughness differences, surface height differences and their combinations. HairTouch consists of two pins for the two finger segments close to the index fingertip, respectively. By controlling brush hairs' length and bending direction to change the hairs' elasticity and hair tip direction, each pin renders various stiffness and roughness, respectively. By further independently controlling the hairs' configuration and pins' height, versatile stiffness, roughness and surface height differences are achieved. We conducted a perception study to realize users' distinguishability of stiffness and roughness on each of the segments. Based on the results, we performed a VR experience study to verify that the tactile feedback from HairTouch enhances VR realism.

CCS CONCEPTS

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

KEYWORDS

Haptic; Tactile; Stiffness; Roughness; Handheld Device; Hair; Virtual Reality.

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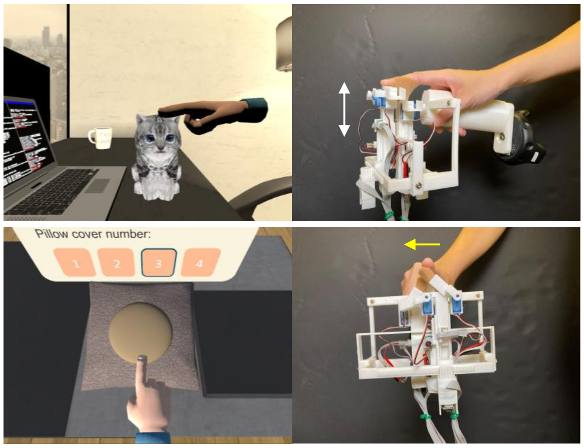

Figure 1: HairTouch provides multilevel stiffness and roughness, and different levels of feedback can be rendered simultaneously, *i.e.*, stiffness differences and roughness differences, with reconfigurable brush hairs.The surface height, can be further achieve based on the pin-based structure.

1 INTRODUCTION

By combining visual and audio feedback from a head-mounted display (HMD) and haptic feedback from haptic devices, users are immersed in a different world in virtual reality (VR). To render realistic haptic feedback, or more precisely tactile feedback, stiffness and roughness are crucial factors when touching virtual objects, *e.g.*, petting virtual animals or pets, or perceiving materials of cloth or furniture in virtual shopping. During touching or sliding on a surface, differences not only in stiffness and roughness but also in surface height, which means the detailed texture height differences on the surface, are essential to render realistic tactile feedback. Therefore, integrating stiffness differences, roughness differences, surface height differences and their combinations into a tactile device is critical to enhance VR experience.

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Many works have been proposed to provide tactile feedback. By switching different physical textures attached to a proxy using a robotic arm, a drone or a spinning wheel, previous methods [2, 5, 46] render the physical texture corresponding to the virtual object to be touched by the users. Although such tactile feedback methods achieve high VR realism, the versatility is limited by the number of physical textures presented immediately. Some other works [8, 15, 21, 22, 27, 28, 36, 38, 39, 42] leverage actuators, including motors, propellers, electrical muscle stimulation (EMS) and vibrotactile actuators, to simulate tactile feedback or generate tactile illusions with various degrees of stiffness and/or roughness. While these methods provide versatile tactile feedback, the realism is limited in actuator simulation due to the delay from deadband and backlash, especially for stiffness simulation with continuously-changing resistive force feedback, as mentioned in [42]. Furthermore, vibrotactile illusions are still different from real tactile feedback. Therefore, how realistic and versatile tactile feedback integrating stiffness, roughness and surface height differences affects users' VR experiences still needs to be explored.

Therefore, we herein propose a pin-based handheld device, HairTouch, to provide various stiffness differences, roughness differences, surface height differences and their combinations using reconfigurable brush hairs. By controlling the hairs' length and bending direction to alter the hairs' elasticity and hair tip direction, each pin provides different stiffness and roughness, respectively. Such a concept of changing physical properties achieves realistic and versatile feedback. Although there is still delay at the tactile level switching prior to the tactile perceiving movement, there is no delay during touching and perceiving at a tactile level [42]. Furthermore, by controlling pins' height, the pins can render various surface heights. Two pins are arranged in line to provide feedback for the two finger segments close to the index fingertip, respectively, and achieve tactile differences in stiffness, roughness and surface height. We conducted a perception study to understand the users' distinguishability of stiffness and roughness on each of the two finger segments close to the index fingertip, respectively. Based on the results, we performed a VR experience study to verify that the tactile feedback with various stiffness differences, roughness differences, surface height differences and their combinations from HairTouch enhances VR realism.

This paper presents the following contributions:

(1) Provision of multilevel stiffness by changing length of hairs for realistic and versatile VR applications.
(2) Rendering of multilevel roughness by altering those hairs' direction for realistic and versatile VR applications.
(3) Exploring users' distinguishability of stiffness and roughness on the two finger segments close to the index fingertip.

2 RELATED WORK

Many methods are proposed in previous research to provide the illusions of touching different materials [11, 20], some of them further focus on controlling and rendering specific properties of tactile feedback, including differences in stiffness, roughness, and surface height. We discuss tactile devices for stiffness and roughness feedback in this section. Furthermore, our proposed device leverages a pin-based structure to control surface height differences, so pin-based devices are also reviewed. Although we change hairs' properties to render tactile feedback, how to fabricate different types of hairs [25, 35] is not focused on here or elsewhere in this paper.

2.1 Tactile Devices for Stiffness Feedback

To provide realistic tactile feedback in VR, using physical objects' properties is a common method. Using the pseudo-haptic concept, Elastic-Arm [3] and FlexiFingers [4] utilize an elastic and metal strips to provide varied degrees of stiffness. Degraen *et al.* [16] further explore how many different forms of tactile feedback a proxy can simulate by fabricating 3D-printed hairs with various structures to enhance texture perception in VR. These methods still require changing the physical objects manually to achieve more forms of different tactile feedback. To overcome the limitation, switching the different physical textures rendered to the users is proposed. Snake Charmer [5] uses a grounded robotic arm to move physical objects or proxies to the corresponding position of the virtual object, so the users can touch, grasp and manipulate the object. Beyond the Force [2] improves the concept on an ungrounded device, a drone, to render the physical objects and achieve better mobility. Haptic Revolver [46] proposes a handheld controller with interchangeable wheels containing multiple physical textures or elements. By rotating the wheel, the corresponding texture is touched by the users' fingertip. Although these methods provide realistic feedback for stiffness and roughness, they generally suffer from a lack of versatility. The number of feedback forms they provide is limited to the number of the physical objects or proxies on the devices. Some other works provide visuo-haptic illusions of stiffness or shape to improve the performance [1, 6, 7, 24], but realism is limited using illusions.

To render versatile stiffness feedback, many works simulate tactile feedback or generate tactile illusions using actuators. For bimanual stiffness feedback, PseudoBend [22] simulates the stiffness of stick-like objects using a force sensor and a voice coil actuator to generate the vibrotactile illusions between hands. Haptic Links [38] presents stiffness by controlling the mechanical brakes on the links between controllers. For stiffness feedback in interacting with objects using a controller, PaCaPa [39] changes pressure to the palm and fingers by actuating two wings using servo motors. HapLinkage [26] renders stiffness feedback by controlling linkage mechanisms using motors. Thor's Hammer [21] uses six propellers to generate forces as pressing on objects with varied degrees of stiffness. For stiffness feedback on an arm and hand, SPIDAR [30] and SPIDAR-W [31] use motors to pull wires and provide six degrees of freedom (DoF) force feedback. Similarly, ExoInterfaces [43] uses two belts to pull the forearm using motors to simulate stiffness feedback. Furthermore, Lopes *et al.* [28] stimulate muscles using EMS to render stiffness feedback when pushing walls.

For stiffness feedback on a finger, CLAW [15] uses a force sensor and a motor to render resistive force when grasping or touching objects with various stiffness. Cutaneous devices use three motors [13, 36] to control a tactor pressing on the fingertip to render stiffness illusions from skin compression. Though these methods provide versatile stiffness feedback, pressing on objects with various stiffness requires different continuously-changing resistive forces, which are difficult to simulate using actuators, *e.g.*, motors, due to the delay from backlash and deadband. This reduces realism, especially in back and forth pressing movement, as mentioned in [42]. Furthermore, vibrotactile illusions are still quite noticeably different from stiffness feedback of physical objects. ElasticVR [42] controls an elastic band's length to generate resistive force for stiffness feedback, and achieves both realism and versatility. However, it only focuses on stiffness feedback on the hand using resistive force. Integrating common tactile sensations, including stiffness, roughness and surface height differences, into a device and providing realistic and versatile tactile feedback on a finger still needs to be explored.

2.2 Tactile Devices for Roughness Feedback

For roughness feedback, the aforementioned material-switching methods [2, 5, 16, 46] render realistic feedback for not only stiffness but also roughness. However, they still suffer from lack of versatility. To render versatile roughness feedback, actuator simulation is also commonly used. TeslaTouch [8], ActivePaD [29] and T-Pad [47] leverage electrovibration and piezoelectric actuators, respectively, to generate vibration on a board to simulate a surface with different roughness. The concept is also used in styli. EV-Pen [44] and RealPen [14] use electrovibration between the pen and board and a linear resonant actuator in a stylus, respectively, to regenerate friction feedback as if one is writing on paper with various roughness using a pen. For VR haptic devices, CLAW [15] utilizes a voice coil actuator to provide vibration for roughness feedback. Fingertip Tactile Devices [36] uses motors to stretch the skin of fingertips to render roughness feedback. Furthermore, RollingStone [27] controls a ball rotation speed beneath a finger to further change the relative slip speed and produces roughness feedback on the finger. Although these actuator simulation methods achieve versatility and vibrotactile feedback better simulates roughness, illusions from vibrotactile feedback, skin stretch or relative motion speed changing are still different from roughness feedback of physical objects. Furthermore, the electrovibration technique requires both a pen and board, which is not proper for VR controllers. Though some methodsachieve both stiffness and roughness feedback, they suffer from either a lack of realism [2, 5, 16, 46] or versatility [15, 36] limitations.

2.3 Pin-Based Structure Devices

Pin-based structure devices are widely used in shape displays for tangible interactions, providing haptic feedback or even for rapid prototyping [40]. inFORM [18] controls 900 pins in a 30×30 layout to achieve dynamically shape-changing user interfaces for facilitating, restricting and manipulating interactions. Based on this design, Materiable [34] improves upon this to simulate three deformable material properties, including flexibility, elasticity and viscosity. inFORCE [32] detects and exerts the force on each pin using closed-loop force control to provide variable haptic feedback. TRANS-DOCK [33] provides changeable transducer modules on a pin-based shape display, *e.g.*, balloons or bending pins, to enhance interactivity. Although these methods also render stiffness feedback, their hardware design is difficult to be miniaturized for ungrounded devices.

For ungrounded devices, shapeShift [37] modifies the hardware design of [18] to implement a mobile tabletop shape display. NormalTouch and TextureTouch [9] proposes a pin-based handheld device with 9 pins in a 3×3 layout on a fingertip to render detailed textures of virtual objects. PoCoPo [48] further utilizes two 3×6 pin arrays on the palm and fingers, respectively, to provide haptic feedback for grasping by the hand. RetroShape [23] uses a 4×4 pin array to implement a shape display on the back of a smartwatch. However, these devices render feedback for objects' shape but not for stiffness. With a simpler hardware design, the current pin-based handheld or wearable devices still do not provide stiffness or roughness feedback.

3 HAIRTOUCH

We present HairTouch, a handheld device to render stiffness differences, roughness differences, surface height differences and their combinations on the index finger to enhance VR realism. HairTouch is built upon the concepts of reconfigurable hairs and pin-based structure. By controlling the hairs' length and bending direction, and pin height, differences in various degrees of stiffness, roughness and surface height are provided, respectively.

3.1 Design Considerations

To render realistic and versatile tactile feedback on the controller in VR, taking the following design considerations into account is essential.

- *Realism.* Rendering realistic tactile feedback when users touch a virtual surface is difficult since it consists of complicated factors, including stiffness, roughness, viscosity, temperature, and surface height. Providing various tactile feedback through a device is essential for realism. However, for continuously-changing force feedback for stiffness, it is challenging to achieve simulations by actuators. Consequently, we choose to control the change of physical objects' properties to render realistic tactile feedback. Furthermore, the gestures or manners used to perceive the tactile feedback should be consistent with the general finger movement when experiencing the surface structure, *e.g.*, pressing to perceive stiffness or moving the finger across a textured surface to perceive the roughness.
- *Versatility.* Tactile feedback consists of various factors as mentioned prior. To achieve versatility, integrating multiple tactile feedback forms on a device is the core idea of our design. Furthermore, allowing users to perceive different levels of tactile feedback is also essential for versatility.
- *Mobility.* To allow users to freely explore in VR, the mobility of the device is essential. Therefore, the proposed handheld device should be lightweight and have a compact form if at all possible.

3.2 Hardware

Based on these design considerations, we have designed and built HairTouch to integrate the tactile feedback, including differences of stiffness, roughness, surface height and their combinations. We tested yarn, a sponge and other physical objects, and finally selected

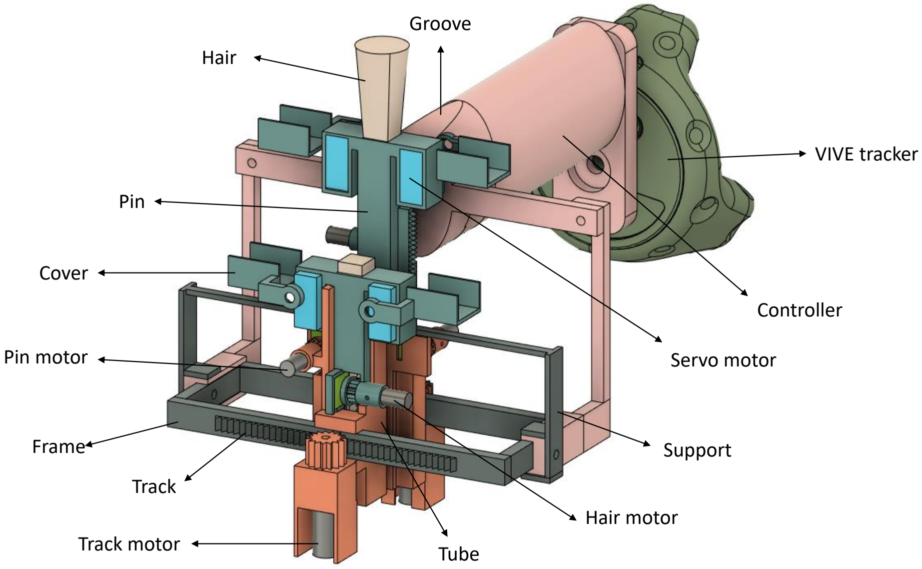

Figure 2: The 3D model of HairTouch.

hairs to provide realistic tactile feedback based on our design considerations. For stiffness, by adjusting the hairs to a longer length, the elasticity of the hairs becomes weaker, which generates the softer tactile feedback when touched or pressed, and vice versa. This property is similar to elastic bands [42] or springs while not following Hooke's law. Furthermore, the hairs with a lower density allow for a larger deformation of the hairs, so the softer feedback is provided. For roughness, by bending the hairs to the smaller angles between the hair tips' direction and the horizontal finger sliding direction, smoother tactile feedback is perceived when the hairs are slid, and vice versa. The hairs with larger angles provide stronger resistive force against the sliding movement is provided, which makes the hairs rougher and feel like burrs. For surface height, the pins are raised higher to provide the tactile feedback of the higher texture on the virtual surface. HairTouch is composed of two tufts of hair, two pins, two tubes, two tracks and a controller. The two tufts of hair are in the two pins, respectively. The two pins control the hairs' length and bending direction in the two tubes. The tubes raise the pins and move on the tracks. The tracks are then connected to the controller. The two pins render tactile feedback to the two finger segments close to the index fingertip, respectively. Such a design provides realistic tactile feedback and achieves the realism design consideration.

For the hairs, to provide wider variations of stiffness and roughness using the same hairs for versatility, some properties should be considered when choosing the hairs. Since HairTouch controls the hairs' length and bending direction to render stiffness and roughness feedback, the hairs should be long enough to provide as many distinguishable stiffness levels as possible for users. Furthermore, for roughness, it is easier and more effective to bend the hairs in where not too close to their roots due to the torque. Therefore, when the hairs are bent, the hairs should remain long enough to be slid. In addition to the hairs' length, the density also affects the stiffness feedback. The denser hairs feel stiffer, and vice versa. When the pins in HairTouch control the hairs' length, the density changes correspondingly; the shorter the hairs, the denser the hairs. Therefore, the hairs with compact hair bases while with fluffy hair tips increase the density variation. For stiffness, the hairs with weaker elasticity are able to render a wider range of stiffness by changing the length. However, the hairs need to be restored to their original state after having been pressed. Therefore, these become the upper and lower bounds of the hairs' elasticity.

Furthermore, for roughness, the finer hairs can be used to render both smooth and rough feedback by bending the hairs in the directions similar and opposite to the horizontal sliding movement, respectively. However, the coarse hairs with prickly hair tips provide a granular sensation on the surface even if the hairs are bent in directions similar to the sliding movement. This limits the coarse hairs from rendering smooth feedback, and restricts the roughness variation. Therefore, the fine and delicate hairs are preferred. Finally, the tufts of hair should be flat, so the surfaces on the top of the tufts of hair are flat when pressed for stiffness feedback. Furthermore, for roughness, when the tufts of hair are bent, the surfaces of the hairs incline as well. The flat tufts of hair have less inclination than that from round or angled tufts of hair in this condition. Moreover, since hair tips are usually the finest part of hairs, trimming the hairs to achieve flat tufts of hair may increase the coarseness, which violates the fine hair requirement. Therefore, it is necessary to find the flat tufts of hair.

We tried hairs of toothbrushes, brooms, paintbrushes, and calligraphy brushes for our design. However, the hairs from these did not completely match the required properties. We further tested

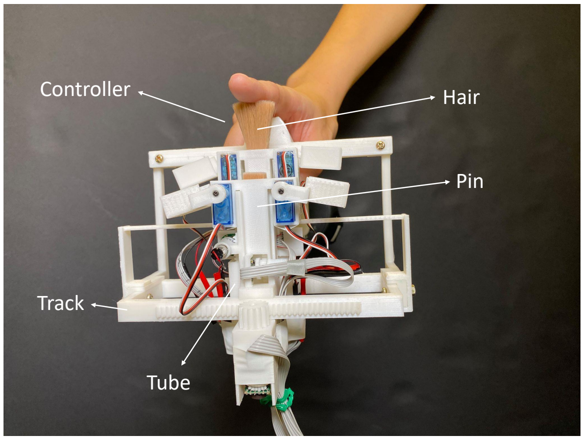

Figure 3: HairTouch held by the user.

different hairs from off-the-shelf cosmetic brushes. Finally, a cosmetic brush with a tuft of hair made of polybutylene terephthalate (PBT) fiber, which is long, fluffy at the tips and compact at the base, properly elastic, fine and flat, thoroughly achieves the requirements and is used in our HairTouch prototype. The process of choosing the hairs fulfills our versatility design consideration.

The length of the hairs from the cosmetic brushes is 36mm, and each base of the hairs is divided into a square sized 10×10mm. The base is then attached to a 3D-printed small plane with a rack beneath it, and this is then placed into the tube-shaped *pin*. A *hair motor* (Pololu Sub-Micro Plastic Planetary Gearmotor with gear ratio 136:1) with a rotary encoder (Pololu Magnetic Encoder 12 counts per revolution) on a pinion is affixed on the pin to move the hair up and down in the pin using this rack and pinion design. To prevent the users from coming into contact with the 3D-printed part of the pin instead of the hair, 4mm is the shortest hair length on the pin. Therefore, the pin controls the hair length from 4mm to 36mm to render varied degrees of stiffness feedback. Furthermore, two servo motors (XCSOURCE RC450) on the two sides of the pin control two *covers*, respectively, to press and bend the hair. The pin can bend the hair within a range of 45 degrees in both directions to render various degrees of roughness feedback.

To raise the pin, a rack is 3D printed on the side of the pin. The pin is further placed in the *tube*, and a *pin motor*, the same type as the hair motor, with a rotary encoder on a pinion is affixed on the tube to move the pin up and down using the rack and pinion design. Raising the pin is not only to provide the differences in surface height but also to compensate for the height of the raised hair, which is described in detail in the following Software subsection of this paper. Therefore, the pin can be raised at most 42mm, and 10mm is for the surface height differences. A *track motor* (Pololu Micro Metal Gearmotor with gear ratio 210:1) with a rotary encoder is affixed on the side of the tube to allow the tube to move along the 3D-printed *track*. Since bending the hair causes that the surface on the top of the hair, used for perceiving roughness, shifts horizontally with an offset, moving the tube on the track compensates for that offset.

The aforementioned design is identically used for the both of the pins. To reduce the distance between two tufts of hair on the finger, the pins and tubes are placed closely on their back sides in a *frame* with the tracks. The tubes may incline backward sometimes since the weight of the tubes is not equally distributed, and there is still space between the tubes as a buffer for smoothly moving on the track and preventing the covers of different pins from colliding with each other. As such, a *support* is affixed on the frame between the tubes and used to prevent this. The frame is further attached to the *controller*. The controller is an elliptical cylinder with a groove in the middle, which allows the users to easily hold the controller while their index finger extends outside of the controller and laying the finger segment close to the palm in the groove. This allows the two segments close to the tip to easily perceive the feedback from the hairs. When the hairs and pins are not raised, the distance between the surfaces of the hairs and the groove is 32mm, which means that all finger segments are of the same height when the hairs are at their maximum length. A Vive tracker is attached to the back of the controller for tracking.

The HairTouch prototype, including the Vive tracker, weighs 320g, which is similar to other handheld devices [15, 27, 48] and achieves our mobility design consideration. Three Dual TB6612FNG motor drivers are connected to an Arduino Mega 2560 board to control the six DC motors in HairTouch. One signal wire for each of the rotary encoders is connected to an interrupt pin on the board for precise motor control. 6V external power is used to supply the hair motors, pin motors and servo motors, and 12V power is used for the track motors.

3.3 Software

Initially, the hairs and pins are not raised and the covers are outward the pins. The tubes are in the middle of the tracks, which are right beneath the index finger but are not touched by the finger. This is defined as the initial state. We further define a plane that the finger can perceive stiffness and roughness feedback on a flat surface as the datum plane, which is in the height of the groove on the controller. Therefore, when perceiving stiffness and roughness feedback on a virtual flat surface, the surfaces on the top of the hairs should be raised to the datum plane. The finger then presses the hairs beneath the datum plane to perceive stiffness feedback, and horizontally slides over the datum plane to perceive roughness feedback. Although finger movement, such as moving speed, affects tactile perception, this also exists in the real world. Therefore, users can perform similar finger movements to distinguish different tactile feedback levels, as in the real world.

To render stiffness feedback, the hair motors raise the hairs higher to increase the hairs' length and provide softer feedback, and vice versa. To achieve this no matter what the hairs' length is, the finger presses on the datum plane when pressing a virtual flat surface, the pin motors raise the pins to compensate for the distance between the raised hairs and the datum plane. Furthermore, since the hairs exactly reach the datum plane when the hairs are at the maximum length in the hardware design, the pins are not raised during this condition. To render roughness feedback, the hair motors adjust the hairs to the length of 31mm and then the servo motors bend the hairs in a direction more similar to and

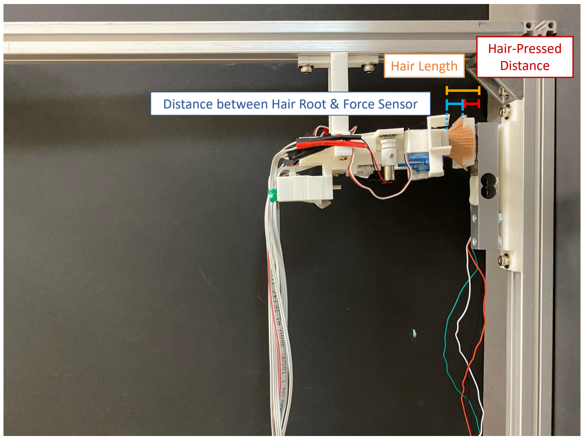

Figure 4: The setup to measure the relationship between hair-pressed distance and resistive force.

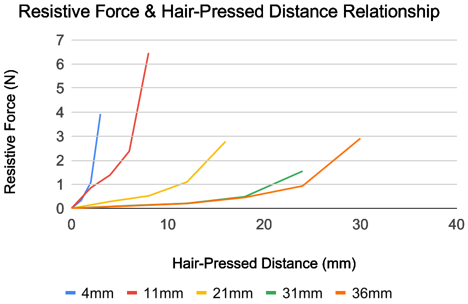

Figure 5: The relationship between hair-pressed distance and resistive force.

different from the horizontal sliding movement to provide smoother and rougher feedback, respectively. When the hairs are bent, the surfaces of the hairs are not only lower than the datum plane but also with a horizontal offset for the finger. Therefore, the pin motors compensate for the the vertical distance between the raised hairs and the datum plane, and the track motors compensate for the horizontal offset simultaneously.

To provide surface height differences above a virtual surface, the pin motors further raising the pins raises the surfaces of the hairs higher than the datum plane. When perceiving a virtual surface with both stiffness and surface height differences or both roughness and surface height differences, the pin motors need to handle the compensation and surface height differences at the same time. When lifting the finger off of any virtual objects, the hairs and pins move down, and their the covers move outward the pins to prevent the finger from having further tactile feedback. PID controllers are used in the control of all the DC motors.

Notably, HairTouch does not render stiffness and roughness feedback simultaneously since the compound feedback from changing properties of the hairs used cannot be clearly perceived by users in our design. However, we usually press an object to perceive the stiffness and slides on the surface of an object to perceive its roughness. Due to the different gestures used, it is quite seldom that these two tactile feedback forms are perceived at the same time using the same gesture. Therefore, HairTouch switches to the appropriate tactile feedback mode based on the current VR scenario. Furthermore, since the roughness feedback from the bent hairs is relative to the finger sliding movement, when the hairs are bent and moved to the datum plane, the users can only slide the finger in a certain direction instead of back and forth to perceive the corresponding roughness feedback. Such a gesture in a sliding, lifting, moving back and sliding sequence is similar to petting or stroking pets.

4 PERCEPTION STUDY

To provide distinguishable levels of the stiffness and the roughness, we conducted a perception study. While a just-noticeable difference (JND) study is a commonly used to find discrimination thresholds [8, 22], a certain intensity should be rendered in each JND stimulus. Since the elastic force from the hairs in both stiffness and roughness feedback continuously changes depending on the users' finger movement, it is not a certain intensity. Therefore, instead of a JND study, we followed the study design in [41, 49] to conduct a perception study to understand the distinguishability of stiffness and roughness on the each of the two finger segments close to the index fingertip, respectively.

4.1 Apparatus and Participants

The HairTouch prototype was held by the participants' dominant hand. A Vive Pro HMD was worn, and a controller was held by the other hand. Unity3D was used to build VR scenes. Noise-canceling earbuds were worn and white noise played to prevent the participants from hearing the noise from the motors. 12 participants (6 male, all right-handed) aged 17 to 32 (mean: 24.25) were recruited.

4.2 Task

A pilot study was conducted to explore the proper examined levels of the stiffness and the roughness from HairTouch. For stiffness, five levels (1, 2, 3, 4, 5) with hair lengths (36mm, 31mm, 21mm, 11mm, 4mm) were chosen for examining the participants' perceptions. At level 1 and 5, the hairs reached the maximum and minimum length, and provided minimum and maximum elasticity, which means the softest and stiffest feedback, respectively. Level 2, 3 and 4 between level 1 and 5 might be distinguishable from each other from a pilot study. Therefore, these five levels were chosen for this study. For roughness, seven levels with hair bending angles (45°, 35°, 25°, 0°, -25°, -35°, -45°) causing the angle between the hair bending direction and the horizontal finger sliding direction (45°, 55°, 65°, 90°, 115°, 125°, 135°) were chosen. Notably, instead of using the values for the bending angle, we used the values for the angle between the hair bending direction and the horizontal finger sliding direction to denote the values of levels of roughness, which was closer to the roughness concept in HairTouch and this prevented ambiguity in regard to different sliding directions. Since our prototype provided the bending angle of 45°, for both levels 1 and 7 with angles of 45° and 135° provided the smoothest and the roughest feedback. Level 4 was the middle level without any bending of the hairs. Levels 5 and 6 might be distinguishable from levels 4 and

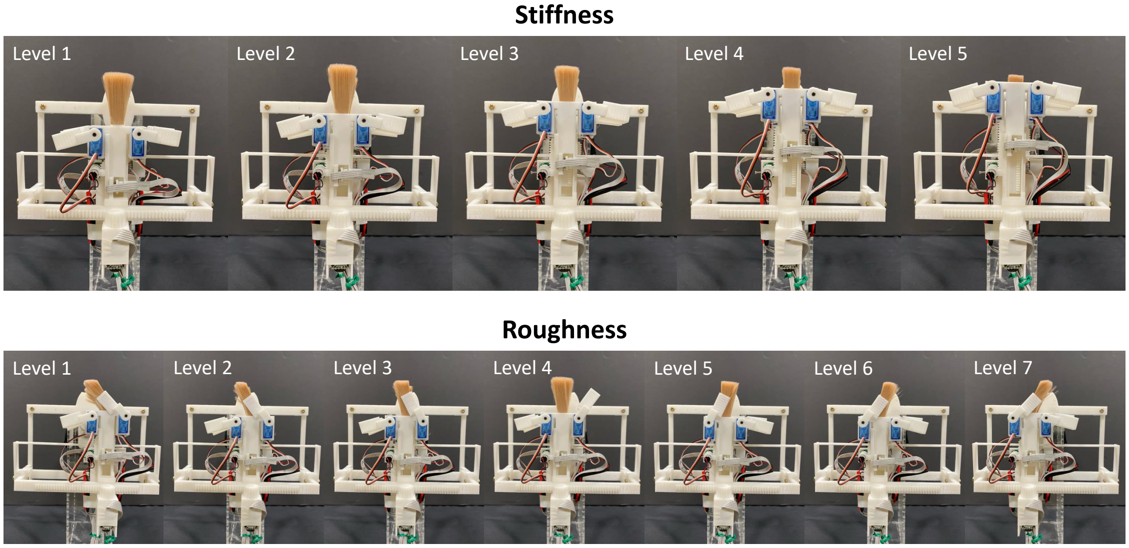

Figure 6: The stiffness and roughness levels examined in perception study.

7 which are distinguishable from each other from the pilot study. Levels 2 and 3 were symmetrical with levels 6 and 5, respectively, and might be distinguishable from each other. The seven examined levels of roughness were therefore determined. Since resistive force plays an important role in both stiffness and roughness feedback, to quantify the feedback, we measured the resistive force of the hairs at different lengths for reproducibility. We attached a force sensor (load cell TAL220 with a HX711 amplifier) and a tube with a pin to an aluminum extrusion frame. To measure the relationship between the resistive force and the hair-pressed distance in different hair lengths, the tube with the pin was repeatedly moved to different distances to the force sensor. The average results are shown in Figure 5. Notably, although the hair spread when close to the force sensor, this is similar to the real conditions of usage.

During this study, different levels of stiffness and roughness generated by HairTouch were presented to the participants. They were asked to perceive the tactile feedback and adjust the visual feedback until the visual feedback best matched the tactile feedback. With the scales in the results, we can statistically analyze the distinguishability of tactile feedback as in [41, 45, 49]. Two VR scenes were built to render visual feedback of various degrees of stiffness and roughness, respectively. For stiffness, a cube with a larger deformation when pressed represented the softer object, and vice versa. For roughness, a plane with a less complex and broader texture represented the rougher surface, and vice versa. This texture was generated by a height map with 128×128 pixels based on the Perlin noise scale in Unity3D. A Perlin noise scale determined how many cycles the basic noise pattern was repeated, which also represented the texture scale in the visual feedback. To further explore the distinguishability of the two finger segments, only one of the two hairs was raised to provide feedback at that moment. We denoted the segment close to the tip as the first segment and the other, further from the fingertip, as the second segment.

4.3 Procedure

Initially, we briefly introduced the HairTouch prototype and how to press and slide one's finger over the hairs to perceive stiffness and roughness feedback, respectively. For stiffness, when the virtual hand contacted a cube in VR, the hairs were raised toward the index finger in the real world. The participants then had to press the hairs with their finger to perceive the stiffness feedback. For roughness, they were asked to slide their index finger in an outward direction only to perceive the feedback, which is a natural gesture to perceive roughness when sliding in a single direction. They were also suggested to move that finger with a larger movement to further move the tracker and make the virtual hand perform a similar gesture. Furthermore, they could freely explore the VR scenes with whole-hand movement. The softest/stiffest and smoothest/roughest feedback forms in both visual and tactile feedback were presented to the participants to allow them to have a rough concept of the mapping ranges. In each trial, the participants perceived the tactile feedback from the HairTouch device on the dominant hand, and adjusted the visual feedback using the controller on their other hand to match the tactile feedback. For stiffness, the adjustable deformation range for the 10×10×10cm cube was between 0 and 3cm, and each adjustment step was 0.06cm. For roughness, the texture scale range was between 28 and 128, and each adjustment step was 2 on that scale. A hint text was shown within the both VR scenes if the visual feedback was adjusted to the maximum/minimum. After the participants adjusted the visual feedback to the best-matching scale, the data were then recorded.

Before each trial started, the hairs and the pins were not raised and the tubes moved to the edge of the track, as a home position. This guaranteed that the pins were out the active range of the finger movement during the level change. The study was a within-subject design. A total of 72 (= (5 (levels of stiffness) + 7 (levels of roughness)) × 2 (finger segments) × 3 (repetitions)) trials were

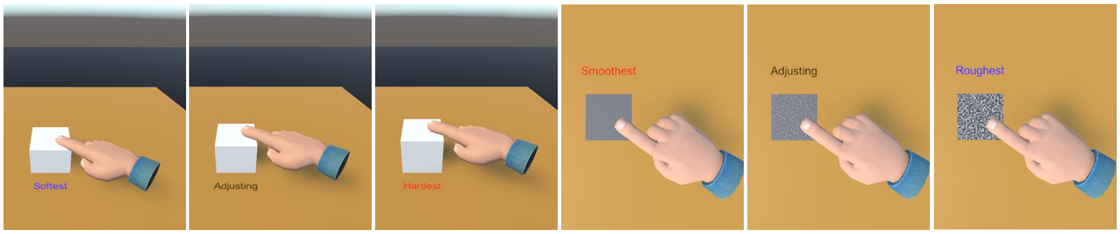

Figure 7: The visual feedback provided in perception study. From left to right is the softest, the middle of the stiffness, the stiffest, the smoothest, the middle of the roughness, and the roughest.

examined by each participant. The order of the examined feedback and finger segments were counterbalanced, and the levels were randomized. After the study, we interviewed the participants to understand how they mapped the visual and tactile feedback. The study took about 90 minutes, including the breaks and interview.

4.4 Results and Discussion

We used an repeated measures ANOVA and Bonferroni correction to statistically analyze the results. For stiffness, significant differences are found for both the first ($F_{4,44} = 139.02, p < 0.01$) and second ($F_{2.24,24.61} = 152.97, p < 0.01$) finger segments. Post-hoc pairwise tests further reveal that significant differences exist among all pairs except between level (1, 2) in stiffness for both segments. As for the roughness, there are significant differences in both the first ($F_{2.15,23.70} = 62.75, p < 0.01$) and second ($F_{1.81,19.91} = 35.84, p < 0.01$) finger segments. Post-hoc pairwise tests show that when the angle is not greater than 90° (levels 1 to 4), there is no significant difference among any pairs. When the angle is greater than 90° (levels 5 to 7), significant differences exist among pairs except between level (5, 6). Furthermore, in this condition (levels 5 to 7), significant differences are found among all pairs at levels 1 to 4. Since the roughness tactile perception is nonlinear [17], we further divided the roughness levels into two groups, levels 1 to 4 and levels 5 to 7, to statistically analyze them. Post-hoc pairwise tests show that significant differences are found among all pairs in levels 5 to 7. These results are consistent for both finger segments.

For stiffness, 6 participants (*P3*, *P5*, *P7*, *P8*, *P9*, *P11*) commented that levels 1 and 2 were difficult to discriminate since the longer hairs at these softer levels allowed the finger to easily press into the tufts of hair. To discriminate the stiffness level, 6 participants mainly based their assessment of the perceived resistive force when pressing the hairs, while 5 participants mainly depended on the hairs' deformation, and 1 participant used the both.

For roughness, 5 participants (*P4*, *P6*, *P8*, *P10*, *P11*) reported that it was challenging to distinguish the roughness variation when the angle was not greater than 90° (levels 1 to 4). We observed that since the hair bending directions are the same as the sliding direction from levels 1 to 3, and level 4 is without bending, the participants sometimes further bent the hairs when sliding, which reduces the differences among these levels. Furthermore, *P3* and *P4* recognized level 4 without bending hairs as the smoothest level rather than level 1 with the most bending hair in their responses. *P10* and *P12* mentioned that they identified the level of roughness based on the resistive force that they perceived. However, since the hairs were fluffy and not bent at level 4, sliding movement was easy to slightly change, which made the perceived resistive force varied. *P10* further mentioned that the fluffy feedback at level 4 sometimes made him/her associate that with smoothness, so the fluffiest level might be regarded as the smoothest level. To distinguish the level of roughness, 5 participants mainly based their assessment on the perceived resistive force when sliding, 4 participants mainly depended on the sensed granular feedback from the hair tips, and 1 participant considered resistive force at levels 1 to 4, and based on the granular feedback at other levels.

Although the distinguishable levels of stiffness and roughness are the same for both finger segments, some differences in distinguishability still can be observed. For stiffness, the participants perceived that level 1 was stiffer than level 2 when using the second segment, while the result was opposite when using the first finger segment. 10 of 12 participants commented that it was easier to discriminate the stiffness with the first segment. 5 of them believed that it was because the first finger segment was more sensitive. 5 of them mentioned that with a wider active range of motion, the first finger segment easily experienced more. For roughness, 9 participants said that the first finger segment performed better in discriminating differences. 6 of them referred it to the sensitivity, and 3 of them concluded that it was due to the active range of motion.

Based on these results and feedback from the interviews, for stiffness, since levels 1 and 2 are indistinguishable and level 1 is having all hairs extruded fully from the pins which may reduce robustness, level 1 is omitted and levels 2 to 5 are distinguishable. Therefore, four stiffness levels (1, 2, 3, 4) with hair lengths (31mm, 21mm, 11mm, 4mm) are provided by HairTouch. For roughness, since levels 5, 6 and 7 with the hairs bent in the direction opposite to the sliding movement are distinguishable, and these also are discriminating from level 1, these four levels are chosen. Therefore, four roughness levels (1, 2, 3, 4) with the angles of 45°, 115°, 125° and 135° between the hair bending direction and the horizontal finger sliding direction are rendered by HairTouch.

5 VR EXPERIENCE STUDY

To observe how the tactile feedback from HairTouch affects the users' VR experiences and investigate whether the feedback from HairTouch enhances VR realism compared with other tactile feedback rendered by other devices, we built two applications and conducted a VR experience study.

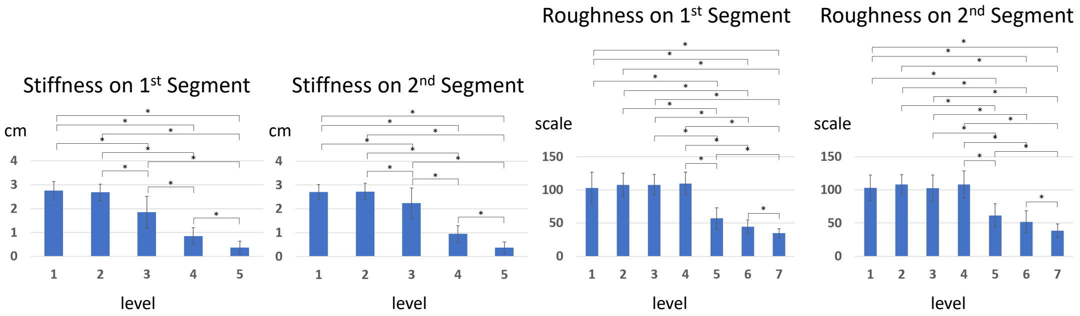

Figure 8: The chart plotting visual feedback corresponding to perceived tactile feedback in perception study.

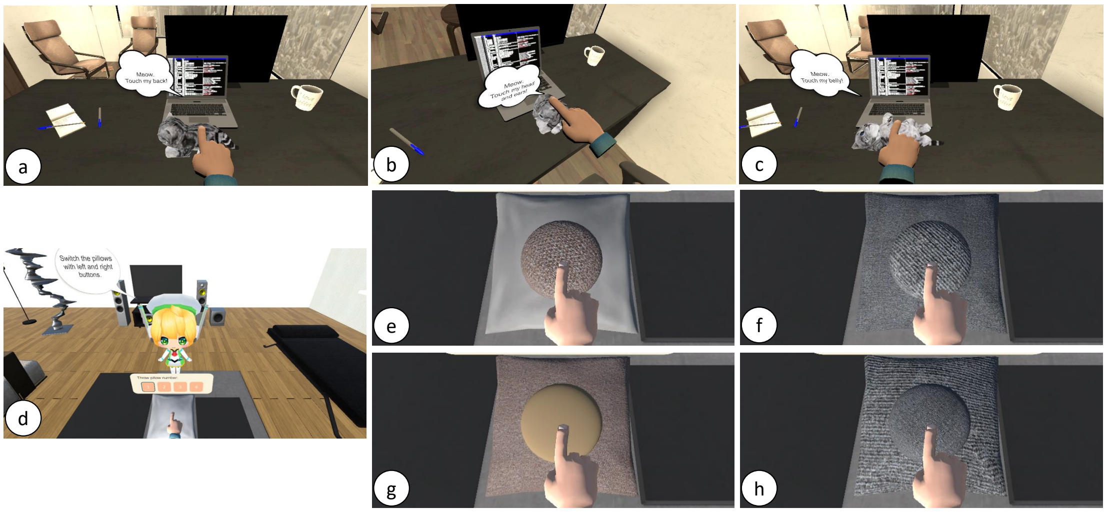

Figure 9: The VR scenes of the applications. (a) Touching the kitten's back. (b) Touching the kitten's head and ear. (c) Touching the kitten's belly. (d) Perceiving the stiffness of the throw pillow. (e)-(h) Perceiving the roughness of the throw pillow covers.

5.1 Apparatus and Participants

The apparatus was similar to that in the perception study, while the headphones of the HMD were used to play the background music of the applications instead of being used for noise-canceling earbuds with white noise. Furthermore, another controller was used to provide vibration feedback for the comparison. 12 participants (5 female) aging 20 to 27 (mean: 23.5) were recruited. One participant was ambidextrous and held the tactile feedback device in the right hand during the study, and the others were right-handed. 2 of them had participated in the perception study but over a week elapsed between the two studies.

5.2 Task and Procedure

Based on the results of the perception study, we built two VR applications, virtual pet and virtual shopping, including feedback from four stiffness and roughness levels, surface height differences and their combinations. In addition to the tactile feedback from HairTouch, we also used the vibration feedback generated by the controller for the comparison. Since vibration feedback is commonly provided in the off-the-shelf devices, it was regarded as a baseline. For stiffness, based on the studies in [28, 42], when the virtual finger presses the surface of a virtual object deeper, and becomes closer to the center of the object, the vibration frequency and amplitude are increased, and vice versa. The slope of the vibration frequency and amplitude variation was larger if the object was stiffer, and vice versa. For roughness, based on [15], if the surface was rougher, the vibration frequency was lower and the amplitude was larger, and vice versa. To maintain consistency between the two feedback methods, the manipulation gestures were the same for both the controller and HairTouch.

5.2.1 Virtual Pet. Initially, the participants stood in front of an office desk in a virtual office. A kitten on the desk, walks toward the participants and asks them to pet it. The kitten changes among three different poses to ask the participants to touch it and pet its four body parts. A stiffness level was assigned to each part, including the cat's ears (level 1), belly (level 2), back (level 3) and head (level 4). The participants could still freely touch the kitten at any point during these poses. Furthermore, the pin height varied corresponding to the surface height, *e.g.*, the ears are higher than the head and the head is higher than the back. The participants were asked to experience each part of the kitten and the combinations of the differences at least once, and were free to explore without time limit.

5.2.2 Virtual Shopping. Initially, the participants sit in a virtual living room. An assistant of the virtual shop arrives and instructs the participants to experience and buy a customized pillow. The participants first experience four throw pillows with four different degrees of stiffness and choose their favorite one. Four pillow covers with different fabrics are then presented. A round pattern with a fabric different from the other parts of the pillow cover is in the middle, and it is higher as the surface height differences. The four pillow covers provided four different roughness level combinations (other, round): (1, 3), (2, 4), (3, 1) and (4, 2). The participants are then instructed to experience all the fabrics and patterns, and make a choice. Finally, the chosen combination is shown.

A total of 4 (= 2 (feedback methods) × 2 (applications)) conditions were experienced by each participant. The order of the feedback methods was counterbalanced. Each condition was experienced for about 5 to 10 minutes. The participants were then asked to rate the realism, distinguishability, enjoyment and preferences on a 7-point Likert scale and give some qualitative feedback after the experiment. This study took about an hour.

5.3 Results and Discussion

For each application, we conducted a Repeated Measures ANOVA to statistically analyze the results. For the virtual pet, significant differences are found in all factors, including realism ($F_{1,11} = 121, p < 0.01$), distinguishability ($F_{1,11} = 28.67, p < 0.01$), enjoyment ($F_{1,11} = 52.14, p < 0.01$) and preference ($F_{1,11} = 46.75, p < 0.01$). For realism, 10 participants said that the vibration feedback was difficult to be associated with the stiffness feedback. On the other hand, 7 participants mentioned that the furry tactile feedback provided by HairTouch enhanced the realism of petting the kitten. For distinguishability, *P4*, *P6* and *P11* said that they kept recalling the vibration patterns to help themselves to discriminate the stiffness since vibration feedback was not intuitive. On the contrary, due to the hairs' physical properties, HairTouch provides natural and intuitive tactile feedback. Overall, no participant reported any issues or confusion about distinguishing between stiffness levels when different stiffness feedback was rendered on the two finger segments, and the surface height differences were also easy to perceive. *P7* and *P9* emphasized that they liked the stiffness and surface height differences, which also enhances the realism. Finally, the participants significantly enjoyed and preferred feedback from HairTouch in the virtual pet application.

For the virtual shopping, significant differences are also found in all factors, including realism ($F_{1,11} = 49.09, p < 0.01$), distinguishability ($F_{1,11} = 39.10, p < 0.01$), enjoyment ($F_{1,11} = 78.67, p < 0.01$) and preference ($F_{1,11} = 71.74, p < 0.01$). For realism in roughness feedback, 10 participants preferred the feedback from HairTouch to the vibration feedback. Although none of the throw pillows and the pillow covers were furry, 7 participants reported that this did not bother them. For distinguishability in roughness feedback, 9 participants recognized the different resistive forces from HairTouch on the surfaces with different roughness. Although *P4* and *P7* said that they enjoyed experiencing the roughness differences, only half of all participants reported that they could clearly perceive the difference between roughness feedback on the two finger segments. This might be caused by the surface height differences. *P5* said that the height difference prevented him/her from perceiving the roughness feedback on two pins at the same time. However, this situation is also in line with the real experiences. Since sliding the finger over the surface with larger height differences might make one of the segments not make contact with the surface, experiencing the roughness differences with slighter surface height differences might enhance their experiences.

The participants significantly enjoyed and preferred feedback from HairTouch to the vibration feedback. *P4* said that it was practical to perceive the tactile feedback online or when virtual shopping, and HairTouch can provide a rough concept of the differences. *P12* said that stiffness and roughness were important factors when picking various products, such as chairs, and HairTouch enabled him/her to experience realistic tactile feedback of the products, which enhanced his/her purchase intentions.

Based on the statistical results and the feedback comments, we can verify that feedback of stiffness differences, roughness differences, surface height differences and their combinations from HairTouch significantly enhances users' VR experiences.

6 LIMITATIONS AND FUTURE WORK

Although HairTouch provided good feedback and experiences for the participants, there are still some limitations. The feedback from the highest stiffness level is still not considered as rigid. However, since the hairs are interchangeable, stiffer materials such as rubber could replace the hairs to provide stiffer feedback. Other materials such as a sponge, wool, and cotton could also provide various feedback. Some other VR scenarios were also mentioned in the perception study interview, including the feedback of flipping a book and touching foam, a sponge, and gauze. These could be further explored in the future. Furthermore, other feedback devices, *e.g.*, vibration motors, could be integrated. Since HairTouch is mainly on the top of a controller, integrating devices on other parts of it is possible. To achieve a larger tactile feedback area, using more tubes as in [48] may even provide whole hand interaction.

Although the gestures for perceiving tactile feedback from HairTouch are based on finger movement, with a VIVE tracker on the device, moving the finger more or less moves the device and makes the virtual hand perform a similar gesture. However, some participants reported that it was a burden to move the hand or wrist in that way. Some participants said that seeing the virtual hand moving in VR when their finger is moving in the real world decreased realism. To handle this, HairTouch may be integrated with Vicon system or controllers with gesture recognition such as a Valve Index controller. Furthermore, if finger tracking is enabled, by swiftly switching the covers to change the bending direction, users are not limited to slide in a single direction anymore.

To enhance mobility, we minimize the surface area of the hairs on each pin to approximately the area of the fingertip. However, during the user study, some participants reported that the surface area for perceiving tactile feedback was too small such that they sometimes

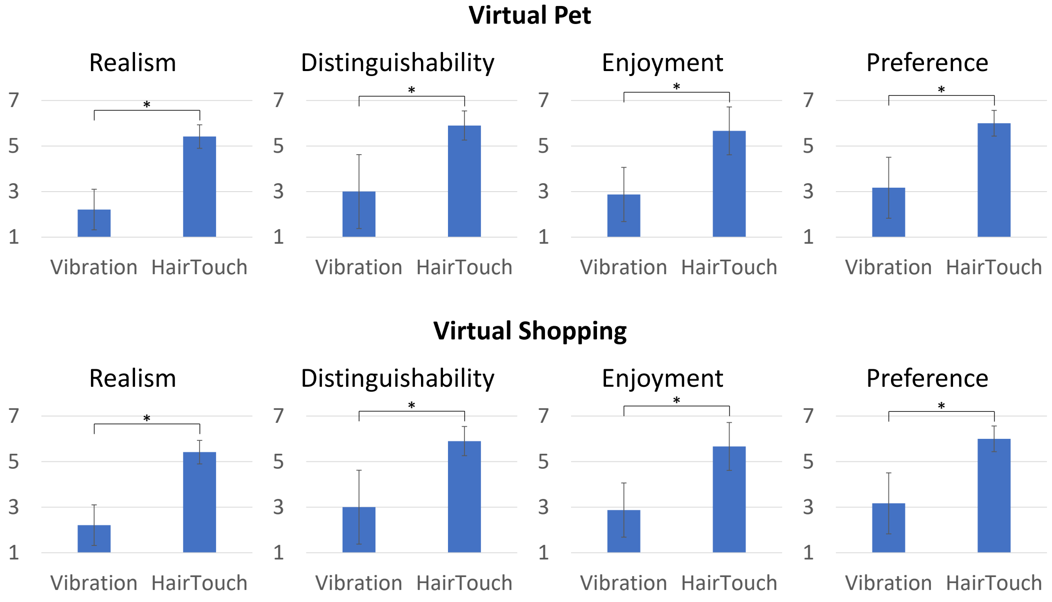

Figure 10: Subjective results of VR experience study (realism, distinguishability, enjoyment, preference) on a 7-point Likert-scale.

exceeded the area and touched the 3D-printed part, which may break immersion. There is a trade-off between the device size and the perceiving area. Some participants suggested that covering the device with furry tape may reduce the effect.

HairTouch cannot render stiffness and roughness simultaneously. However, in the perception study, *P8* and *P10* felt the surface smooth and soft in roughness levels 1 to 4, but rough and stiff in levels 5 to 7 due to the resistive force. It seems possible to render these feedback types simultaneously. However, these are dependent on the current version. Perhaps, by combining some unexplored properties, such as hair density, the goal may be achieved.

During mode or level switching, the delay issue is a problem for HairTouch. Integrating hand trajectory estimation methods [10, 12, 19] may reduce the effect from the switching delay.

7 CONCLUSION

We herein propose HairTouch, a handheld device providing stiffness differences, roughness differences, surface height differences and their combinations based on the physical properties of hairs in VR. Using the motors to change the hairs' length and bending angle and the pins' height, multilevel stiffness and roughness are provided, and the surface height differences are also achieved. Using the pin-based structure with two pins, various tactile feedback can be rendered independently to the two finger segments. The perception study found that there are four distinguishable levels in both stiffness and roughness, respectively, provided by HairTouch. The VR experience study with two applications verifies that the feedback from HairTouch significantly outperforms the off-the-shelf vibration feedback in terms of realism, distinguishability, enjoyment and preference. Therefore, tactile feedback from HairTouch indeed enhances users' VR experiences.

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