FrictShoes: Providing Multilevel Nonuniform Friction Feedback on Shoes in VR

Chih-An Tsao, Tzu-Chun Wu, Hsin-Ruey Tsai, Tzu-Yun Wei, Fang-Ying Liao, Sean Chapman, and Bing-Yu Chen

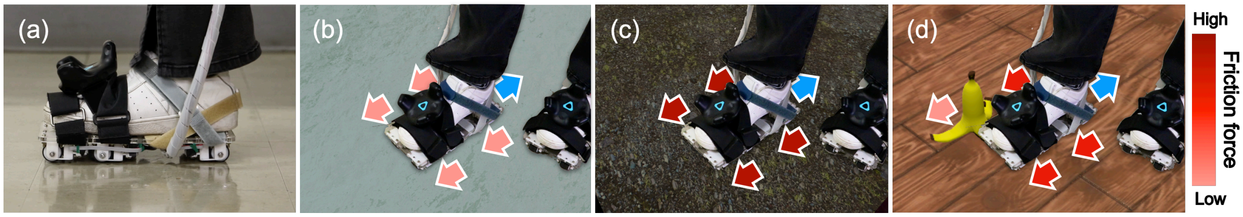

Fig. 1. FrictShoes provide multilevel nonuniform friction force feedback to the feet using wheels and brakes. Users perceived less friction force feedback when walking on an ice field (b) than on a gravel road (c). When stepping on a banana peel (d), they perceived less friction force feedback from that portion of their foot. The blue arrows indicate the users' force applied to the ground, while the red arrows represent the friction forces rendered upon different points of the foot; the darker the arrow's color, the stronger the force is.

Abstract— Many haptic feedback methods have been proposed to enhance realism in virtual reality (VR). However, friction on the feet in VR, which renders feedback as if walking on different terrains or ground textures or stepping on objects is still less explored. Herein, we propose a wearable device, FrictShoes a pair of foot accessories, to provide multilevel nonuniform friction feedback to feet. This is achieved by the independent functioning of six brakes on six wheels underneath each FrictShoe, which allows the friction levels of the wheels from each to be either matched or to vary. We conducted a magnitude estimation study to understand users' distinguishability of friction force magnitudes (or levels). Based on the results, we performed an exploratory study to realize how users adjust and map the multilevel nonuniform friction patterns to common VR terrains or ground textures. Finally, a VR experience study was conducted to evaluate the performance of the proposed multilevel nonuniform friction feedback to the feet in VR experiences.

Index Terms—Haptic feedback, friction force, force feedback, on feet, virtual reality, wearable device

1 Introduction

Haptic feedback plays an important role in virtual reality (VR) interactions, since it enhances immersion, realism and users' VR experience. Many types of tactile and force feedback have been discussed in VR haptic research. Friction is a common physical effect in our daily lives. Several devices provide such feedback to the hands or fingertips when touching or writing on objects or surfaces with different textures or roughness. However, none of them explore friction feedback for feet as walking on different terrains in VR, *e.g.*, walking on a tarred road, meadow, snow, sand, mud or even stepping on rough rocks or slippery oil or banana peels, which is important when exploring different VR environments. This could be used for not only VR terrain exploration or games but also in medical rehabilitation for walking or fall prevention [30], sports training or walking simulation training in different environments [56], *e.g.*, simulating walking on ice. Therefore, we explore how friction feedback to the feet affects users' VR experiences.

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To render friction feedback, previous methods leverage vibrotactile actuation, electrovibration, relative motion speed changing and skin stretching [2, 21, 34, 39, 40, 55] to generate virtual friction and cause users to perceive illusions of different friction feedback when touching and writing on surfaces with different textures. Switching materials [1, 54] is an alternative to provide real friction feedback when the finger touches or moves on a surface. However, these methods generally focus on fingertips and hands. For haptic feedback on feet, previous works utilize vibrotactile actuation, motor actuation, electromagnet slider, and fluid viscosity control [19, 33, 37, 56], to render different textures, roughness, viscosities and heights of various terrains. Some other methods control wheels or pull strings on shoes [14, 15] to deal with the locomotion issue when users walk in VR. Although some approaches [25, 30] use floor tiles with balls and pins and a detachable outsole on a shoe to render friction feedback, current haptic feedback methods for feet generally either do not focus on friction feedback or are limited to grounded devices or one-time only feedback. Thus, how friction on feet enhances VR realism still needs to explore on wearable devices especially for multilevel nonuniform friction feedback.

Herein, we propose FrictShoes, a device consisting of a pair of foot accessories, to provide multilevel nonuniform friction force feedback to feet in VR (Figure 1). Each FrictShoe consists of six wheel sets in a 3×2 layout. A wheel and a brake controlled by a motor comprise a wheel set. The wheel sets are attached to a board with adjustable Velcro bands. When the brakes block the wheels at different levels, multilevel friction is generated as the user steps on ground with different textures in VR. Furthermore, by blocking the wheels at different levels independently, *e.g.*, braking four front wheels and releasing two rear wheels, two friction levels are rendered by the two parts of the FrictShoe as the user steps on an object, achieving nonuniform friction feedback. We conducted a magnitude estimation study to observe how users estimate the friction force magnitudes (or levels) and further understand users' friction force level distinguishability with their feet. Based on the results, we further performed an exploratory study to understand how users adjust and map the multilevel nonuniform patterns to common VR terrains or ground textures. Finally, we conducted a VR experience study to evaluate the performance of the proposed multilevel nonuniform friction feedback on shoes in VR experiences.

The contributions are described as: (1) designing and implementing a wearable device to provide multilevel nonuniform friction force feedback to the feet; (2) understanding users' friction force level perception via their feet; (3) realizing users' mapping consensus between common VR terrains or ground textures and the nonuniform friction patterns; and (4) evaluating the performance of the proposed friction feedback in VR experiences while proposing some applications for FrictShoes.

2 RELATED WORK

2.1 Haptic Feedback in Virtual Reality

To render realistic haptic feedback in VR, a motor-driven mechanism is a common implementation option. Some methods [3, 4, 7, 41, 48] leverage motors to push, pull, or press users' fingers, hands, or heads to render texture, shape or stiffness of virtual objects or various force feedback. Instead of providing haptic feedback directly from motors, some other works [6, 9, 10, 31, 35, 45–47, 57, 58] uses motors to control brakes, spinning wheels, elastic bands, weights and fans to provide resistive force, impact, weight changing illusion, inertia and oscillation feedback on users' hands and heads. Alternatively, some recent works [12, 16, 17, 32] utilize propellers to render pulling, impact and weight changing force feedback on users' hands. Electrical muscle stimulation (EMS) is an alternative to provide resistive force, impact or weight changing feedback on users' hands and limbs [22, 23]. To render shape props of virtual objects, light-weighted and space-saving pneumatic airbags are also used in some works [43, 44]. In sum, these haptic methods are used to enhance VR realism.

2.2 Friction Feedback Devices

To render textures with different friction in VR, a rather straightforward method is to leverage real materials via the devices. Beyond the Force [1] attaches two pieces of fabric to the two opposite sides of a drone. The drone rotates its different sides to the users and allows them to touch and feel corresponding textures in VR. Haptic Revolver [54] attaches a wheel with several materials on a VR controller. When users touch and move along a surface in VR, it spins the wheel to provide corresponding shear force and textures. Although the materials are interchangeable on these devices for different VR scenes, the numbers of materials attached to the material-switching devices are limited.

A common alternative is generating friction illusion to simulate different textures. TeslaTouch [2] leverages electrovibration to produce various electrostatic friction and provides a broad range of tactile sensations in multitouch interactions. Similarly, EVpen [52] controls electrostatic friction between its pen and touchscreen, and provides pen-on-paper-like writing tactile feedback, which is lacking when writing on a touchscreen. RealPen [5] records and analyzes the oscillation between a pen and paper, and then uses a linear resonant actuator and speaker to generate friction oscillation and a corresponding sound when the user writes with it. T-pad [55] and ActivePad [26] use piezoelectric actuators to produce an air squeeze film effect between a finger and surface and vary surface friction. By stretching the skin on a fingertip, a fingertip tactile device [34] uses three tiny motors to move a tactor and provides friction illusion. RollingStone [21] rotates a ball to generate different relative slip speeds to produce the illusion of friction as using a finger to slip across different virtual surfaces.

Braking control is another common way to provide friction feedback. Haptic Links [38] leverages motors to compress ball-and-socket elements and interwoven layers at different levels to provide varied friction feedback between VR controllers. Frictio [11] controls a brake on a ring, so users perceive passive kinesthetic force feedback with different friction forces as a new output channel of smart rings. Aarnio [42] controls a disc brake and brake handles on wheels to provide resistive force feedback and friction when users rotate and roll the chair. CapstanCrunch [36] proposes a friction-based capstan-plus-cord, variable-resistance brake mechanism to generate resistive force feedback using a small internal motor. Such a design allows the controller to provide human-scale touching and grasping haptic sensations in VR without requiring large and power consumptive actuators. Current research generally uses material-switching, friction illusion and braking control mechanisms to provide friction feedback. However, none of these methods investigate friction rendered on the feet.

2.3 Haptic Feedback on Feet in Virtual Reality

For haptic feedback on feet to enhance VR realism, Level-ups [33] designs adjustable motorized-stilts under its boots. The stilts are locked at different heights to provide users with haptic feedback as stepping on virtual stairs. Snow Walking [56] leverages motors, distance sensors, electromagnets and vibration speakers placed on the feet to control the pulling and pushing force and reproduce the unique feelings of walking in deep snow. In addition, a thin bag filled with potato starch is used to provide crunching feedback as stepping in deep snow. By attaching two magnetorheological fluid (MR fluid) actuators between a shoe and sole, RealWalk [37] varies magnetic field intensity to rapidly change MR fluid's viscosity and provides deformation as if contacting different ground materials, such as walking in snow, mud or sand. Multisensory feedback is also discussed in haptic feedback on the feet. Audio-tactile interfaces [8,24,27–29,49–51] combine audio and vibrotactile feedback or magnetic field sensitive elastomers to achieve multisensory feedback. Although these methods provide varied haptic feedback on the feet, they do not focus on friction feedback. Two types of variable-friction floor tiles are proposed [25] using an array of balls and an array of sharp pins in the tiles, respectively. By pressing the cover plate of the floor tile with the ball array, or raising the pins sticking out of the other type of the floor tile, the friction level is changed. Rasmussen and Hunt [30] propose a wearable device with a detachable outsole. By detaching the high friction outsole, a sudden slip feedback is generated for a single use only. These methods explore friction feedback on the feet, but they are either grounded devices or limited to one time feedback only.

Some other methods use haptic feedback rendered on the feet to maintain users in the same position as locomotion mechanisms in VR. Powered Shoes [14] uses motors in a backpack to control rollers underneath shoes through flexible shafts and achieves active roller skates. When users walk, Powered Shoes cancels the displacement. String Walker [15] mounts motor-pulley mechanisms on a turntable which pull strings on shoes to eliminate the step. HapStep [18] uses two motors to control a plate on an extremely low friction rail for each foot. When walking in VR, it provides longitudinal friction force feedback on the soles when the users are sitting in the real world. Friction feedback to the foot is also used for feet pointing. Free the hands [13] uses friction feedback to enhance feet pointing performance by controlling a high-friction material protruding on a sole and shows that the throughput is competitive with a range of hand controlled device. Although these methods more or less change the friction between the shoes and the floor, they focus on VR locomotion and feet pointing issues instead of VR realism. However, their mechanisms are still worthwhile for consideration when designing our devices.

3 FRICTSHOES

We propose wearable devices, a pair of FrictShoes, to provide multilevel nonuniform friction force feedback to the feet to enhance VR realism. FrictShoes renders various friction feedback when users walk on different terrains or ground textures, or even step on objects with different textures, *e.g.*, a banana peel. Although there are several haptic feedback factors when walking or stepping on terrains or objects, including shape, size, viscosity, stiffness, roughness, height and friction, we focus on the friction factor in this paper. Based on the friction formula ($f = \mu N$, where f means friction force, μ is the coefficient of friction (COF) and N is normal force), the friction force is proportional to the normal force. However, the weight of users differs thus producing different than normal forces. Even for a single user, s/he produces different normal forces when s/he is in different phases of

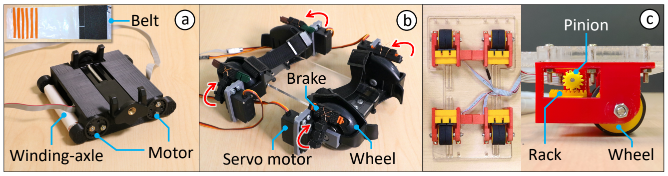

Fig. 2. The preliminary prototypes used the (a) material-switching concept, (b) braking control mechanism, and (c) rack and pinion mechanism.

their gait cycle, *e.g.*, heel strike, stance and toe-off phases. Hence, it is difficult to control the normal force to render friction feedback. Thus, FrictShoes renders different COFs between the FrictShoes and the floor to render friction when stepping on varied textures.

3.1 Design Considerations

To provide realistic friction force feedback, the following design considerations were taken into account: (1) *Multilevel Friction Force*: when stepping on the ground or objects with different textures, users should perceive friction forces depending on the COF between the shoes and textures. Such friction feedback provides users with realistic VR walking experiences. (2) *Nonuniform Friction Feedback*: when stepping on an object with a texture different from the ground using a portion of the foot, *e.g.*, stepping a banana peel on a tarred road, the users should perceive different friction forces at different points on the foot. Therefore, uniform friction force change, which means a consistent friction level on the foot, is insufficient. Independently controlling friction force levels at different points of each shoe, *i.e.*, nonuniform friction feedback, is essential. (3) *Form Factor*: the devices' form factor is an important issue especially for devices involving the feet. If it is rather different from conventional shoes, users' walking experiences could be severely interfered with. Hence, how to design a device for the feet with a similar form factor, including height, weight and size, to conventional shoes is challenging. (4) *Mobility*: to freely explore in VR, ungrounded wearable devices are preferable for mobility. Furthermore, the size and weight of the devices should not be too bulky and heavy to affect the users' experiences. (5) *Adjustability*: since users have differing foot and shoe sizes, adjustable devices are required. This not only allows users with different shoe sizes to wear the device, but also guarantees them to perceive the same haptic feedback.

3.2 Hardware Implementation

To render varied friction feedback on the feet, we tried three preliminary prototypes, using the material-switching concept [1,54] (Figure 2 (a)) to indeed render various COFs, and the braking control concept [11,38,42] (Figure 2 (b)(c)) by pressing the brakes on the wheels to generate the resistive force via the shoes as if stepping on ground textures with different COFs. However, these were either limited regarding friction types in the material-switching method, or too heavy, bulky, high and inflexible, which caused the unconventional walking experiences. Thus, to achieve versatile friction feedback, braking control is better utilized.

We improved the design and built the current FrictShoes prototype. Each FrictShoe consists of a laser-cut acrylic board and six wheels sets underneath the shoe (Figure 3). Each wheel set comprises a wheel, a brake and a DC motor in a 3D printed frame, which is further attached to the acrylic board. For the wheels, the size (diameter) is small enough to maintain conventional walking experiences, and the wheels are robust enough to support pressure from walking or even quick movements during VR games. Since wheels from commercial roller skates or inline roller skates are too large, we fabricated the rims (diameter: 20mm and width: 20mm) using a 3D printing process with the PLA material. To provide sufficient friction on the wheels, two Mini 4WD rubber tires (Tamiya Low Profile Tires, width: 9 mm) are side by side affixed on each rim, which add about 6 mm to the wheel diameter. Hence, the diameter of the wheels is 26 mm. Two bearings are embedded in the two sides of each wheel rim, respectively, so the wheel smoothly rotates on an axle (M4 threaded rod), which is affixed to the frame with nuts.

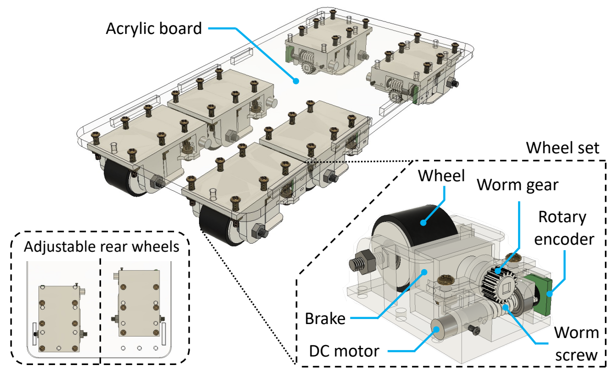

Fig. 3. The 3D model of the current FrictShoes prototype.

For the brakes, a rubber bicycle brake pad is affixed to a 3D printed brake shell. The shell is controlled by a DC motor (Pololu Sub-Micro Plastic Planetary Gearmotor with gear ratio 26:1) using a worm drive mechanism. The worm drive mechanism is using a worm screw, which is a gear just like a screw, to drive a worm gear, which is like a spur gear. A worm screw is affixed to the shaft of the DC motor, and a rotary encoder (Pololu Magnetic Encoder 12 counts per revolution) is attached to the other side of the worm screw. The worm screw drives a worm gear with 18 teeth set perpendicularly, which is further affixed to an M4 screw (length 10mm and thread pitch 0.5mm). A nut on the screw is embedded into the brake shell. Hence, when the screw rotates, the brake shell slides in a track as a linear actuator and presses the wheel rendering different resistive forces, achieving our multilevel friction force design consideration.

In fact, two worm drives are in this brake design. The worm drive of the worm screw and worm gear allows the motor and screw to be placed perpendicularly to reduce the size of the wheel set. The worm drive of the screw and nut, which is used as a linear actuator, has a self-locking property. Hence, after moving the brake to the target position, the motor is not actuated. Furthermore, compared with the rack and pinion mechanism, the worm drive has little backlash. Regarding brake control precision, the motor rotating the worm screw by 18 revolutions drives the worm gear (18 teeth) to rotate for 1 revolution, which further makes the screws (thread pitch 0.5mm) rotate 1 revolution and move the brake 0.5mm. Since the rotary encoder 12 (counts per revolution) is attached to the motor shaft, our brake control precision is 1 / (36 $(18 \times (1/0.5)) \times 12) = 1/432 = 0.0023$mm. Furthermore, by manually rotating or moving between the screw and nut, the worm gear and worm screw, and the motor with the gearbox, and video recording these, we separately obtained the backlashes of these three parts. We further computed the backlash of the brake via the gear ratios and obtained about 0.0163 mm, which is about 7 counts from the rotary encoder.

For the acrylic board, we reduced the thickness of the board from 8mm in our preliminary prototype to 5mm to reduce the height and increase the flexibility of FrictShoes based on the pilot study comments of the preliminary prototype. The size of the board is 130×255mm and it is flexible but robust enough when users stand or step on it. To support the thinner board, four wheel sets were not enough. Six, eight or more wheel sets were considered. Although more wheel sets render higher spatial resolution of friction feedback to the feet, equipping more wheel sets increases the size and weight of the device, which violates our form factor and mobility design considerations, and may change the conventional walking experiences. Furthermore, we performed a pilot study for the preliminary prototype in Figure 2 (c) and found that the average friction pattern recognition rate of four wheels was about 73%. This indicates that users could roughly recognize friction patterns with four wheels but might struggle to clearly recognize patterns with more wheels. In addition, we tried to attach eight wheel sets on the board, which made the device heavy and inflexible. Therefore, as a trade-off between friction spatial resolution and device weight and flexibility, we

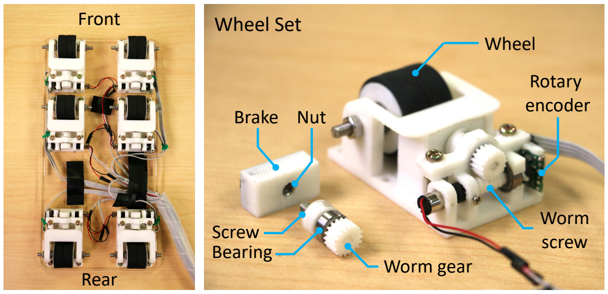

Fig. 4. The FrictShoes device. The bottom view of a FrictShoe (left) and the wheel set with an exploded view of its parts (right).

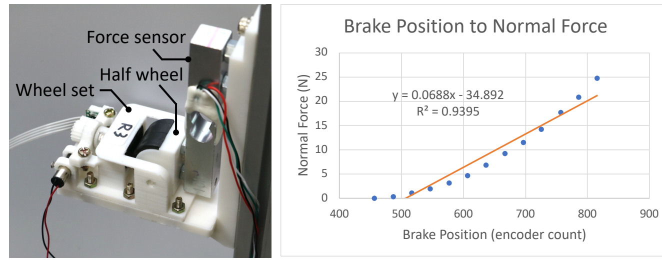

Fig. 5. The setup for measuring normal force (left) and the relationship between the brake position and normal force (right). The sampled force at different positions and the linear regression line are shown.

choose six wheel sets in a 3×2 layout with the three rows of wheel sets approximately beneath the toes, ball of foot and heel (Figure 4 (left)). This provides reasonable weight, support and flexibility.

Due to the size of the wheel set, the distance between the first two rows is 64.5mm. To achieve our adjustability design consideration for users with various shoe sizes, the third row is adjustable, so the distance between the first and third rows could be either 202.06mm or 216.35mm. Furthermore, the distance between the left and right columns is 73mm. Each FrictShoe is affixed beneath a normal shoe using four Velcro belts and a Vive tracker is attached to the user's instep for foot motion tracking. The height of each FrictShoe is about 35mm and the weight is about 530g without the Vive tracker and Velcro belts. The devices' size, height and weight are generally smaller and lighter than other current haptic devices for the feet [33, 37], which reduces the interference upon walking experiences and achieves our form factor and mobility design considerations. Thus, although the form factor is similar to roller skates, users still can walk in conventional poses as in Powered Shoes [14], which is also proven in our studies. The six motors are controlled by three motor drivers (Dual TB6612FNG) connected to an Arduino Mega board for each FrictShoe. Since each wheel set is controlled independently, our nonuniform friction feedback design consideration is achieved. A 6V power supply is required for the motors. The Arduino boards and drivers are wrapped up in a 138.6×87×38 mm laser-cut acrylic case, which is mounted on a Velcro waist belt.

3.3 Calibration

To render any given friction force level from the different wheels by controlling the brakes, calibration is required between each wheel and brake. Using a rotary encoder in the wheel set, we obtain a relative distance for moving the brake to its initial position when the system starts. However, the brake's initial position is not fixed. Therefore, we have to define an *absolute reference position* and automatically calibrate the brake to that position in the beginning. The brake is gradually moved away at a motor speed 1250 RPM (3 V power supply) until it reaches to the end of the screw. If the encoder does not detect any change in 1 second, which means the motor speed less than 5 RPM, the position is defined as the absolute reference position. Therefore, the calibration error of the absolute reference position is less than 1 rotary encoder count. After the calibration, when the system starts, the brakes are independently controlled by the motors with PID controllers. By moving the brakes to the corresponding positions, FrictShoes provides multilevel nonuniform friction force feedback to the feet.

Although the same materials are used for the wheels sets, there are still some small differences among brake pads and wheel tires, respectively, *e.g.*, in regard to thickness. To control all brakes to render the same resistive force and further generate the corresponding COF for friction feedback, we measured the normal force from each brake, which is relative to the resistive force, and obtained the relationship between the brake position and the normal force applied to the wheel. We built an aluminum extrusion frame and affixed a force sensor (TAL220 with a HX711 amplifier) and the wheel set without its wheel on the frame for taking measurements. A half wheel with a tire was affixed on the force sensor in the removed wheel's position of the wheel set. The wheel set and force sensor were not connected to each other. Such a setup (Figure 5 (left)) allowed us to measure the normal force applied to the wheel when the brake gradually pressed on it.

Before measuring this relationship, we found the *critical position*, which is the brake position where the brake would contact with the wheel if it was moved toward the wheel any further, for each wheel set. After moving the brake from the absolute reference position to the critical position, by gradually moving the brake position toward the wheel and recording the data from the force sensor, the linear regression line for the relationship was further computed (Figure 5 (right)). Therefore, with the regression line from each wheel set, after the wheel was re-installed to its wheel set and the critical position was found, the relationship between the normal force and brake position was known using this calibration just once. The precise multilevel friction feedback control on each wheel set was then enabled.

4 Magnitude Estimation Study

To observe how users estimate friction force magnitudes (or levels) and further understand users' friction force level distinguishability, we conducted a magnitude estimation study. A just-noticeable difference (JND) study is usually used to observe distinguishability of stimuli intensity. However, the friction force is not of a certain intensity but rather it is affected by the normal force applied to the shoes as mentioned prior, and the feedback that FrictShoes device provides is as if stepping on ground textures with varied COFs. Hence, instead of a JND study, we conducted a magnitude estimation study as in the previous works [20, 46, 53, 58]. In this study, we focused on force magnitude estimation, so the force level of all wheels on a FrictShoe were the same, which means that uniform friction force was examined.

4.1 Apparatus and Participants

The FrictShoes device was worn. For safety, knee pads were worn as well. A Vive Pro Eye HMD was worn and a controller was held by the participants. We built a VR scene using Unity3D and SteamVR 2.0. Brown noise was played from noise-canceling earbuds to cancel the noise from the motors (Figure 7 (left)). The wires were bound and hooked to the ceiling to prevent the participants from stumbling over the wires. 12 participants (9 males) aged 22-27 (mean age: 23.67) were recruited, and all of them had VR experience before. Only one participant with feet sized 23.5cm used the smaller layout for FrictShoes.

4.2 Force Stimuli

To determine the friction force levels examined in this study, we performed a pilot study. The minimum and maximum friction force levels were defined as when the wheels freely rotated and the brakes were completely engaged, respectively. When freely rotating, the brakes did not contact with and applied normal force (0N) to the wheels. Therefore, we used the critical position of each brake to render the minimum force level. For the maximum force level, the brakes could exert normal force up to 25N to completely brake the wheels, which was then defined as the maximum force level. To find the proper examined force levels, we followed the procedure in Algorithm 1. We searched the minimal friction force which was distinguishable from the previous level and set it as a new force level using a method similar to the binary search. The search process ended when the search range (L_{low}, L_{high}) was at less than 20 rotary encoder counts (about 0.91N of normal force on average) which was larger than twice of the error caused by the backlash.

Algorithm 1 Determine Force Levels

Given L_{max} and L_{min} as the maximum and minimum force levels.
$i = 1$
$L_1 = L_{min}$
while user can distinguish between L_i and L_{max} **do**
  $i = i + 1$
  $L_{low} = L_{i-1}$
  $L_{high} = L_{max}$
  while distance$(L_{high}, L_{low}) \geq 20$ rotary encoder counts **do**
    $L_{mid} = (L_{low} + L_{high})/2$
    if user can distinguish between L_{i-1} and L_{mid} **then**
      $L_{high} = L_{mid}$
    else
      $L_{low} = L_{mid}$
    end if
  end while
  $L_i = L_{high}$
end while
if the wheels are not fully braked at L_i **then**
  $L_i = L_{max}$
end if

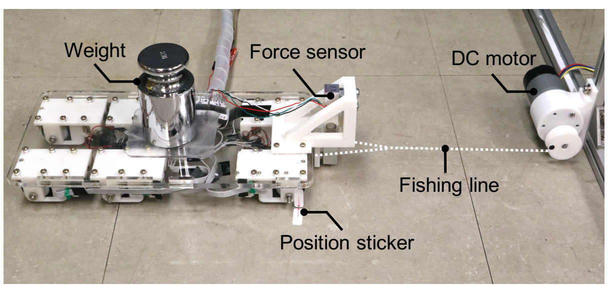

Fig. 6. The setup for measuring maximum static friction force.

Based on our procedure, five friction force levels (1, 2, 3, 4, 5) with the normal forces (0N, 9.38N, 12.3N, 15.48N, 21.43N) from the brakes were found and used as force stimuli in this study. Except level 1, the brake position of each level was obtained from the regression line of each wheel set. The brake position of level 1 was the critical position.

Since we intended to render friction force feedback as if walking on ground textures with different COFs, we regarded a FrictShoe with different resistive forces as the device with different textures underneath it, which achieves the illusion of various COFs. We measured the maximum static friction force to obtain the coefficient of static friction between the device and floor, since we observed that instead of kinetic friction force, static friction force was mainly used to distinguish ground textures in a pilot study. Although resistive force feedback from brake control was still different from a device with various textures for the COF measurement, the measurement quantified the feedback of the five friction force levels as various COFs from FrictShoes.

For the measurement, we leveraged a DC motor (Pololu 131:1 Metal Gearmotor) affixed on an aluminum extrusion frame to stably pull a FrictShoe with a force sensor (TAL220 with a HX711 amplifier) via a fishing line (Figure 6). A 1000g weight was placed on the FrictShoe. A pair of position stickers was attached to the FrictShoe and ground, respectively, to show whether it had moved. After adjusting the brakes to the testing force level, and the fishing line was loosened to ensure that no force was applied to the force sensor, the motor gradually pulled the device. If the force magnitude from the sensor was stable and

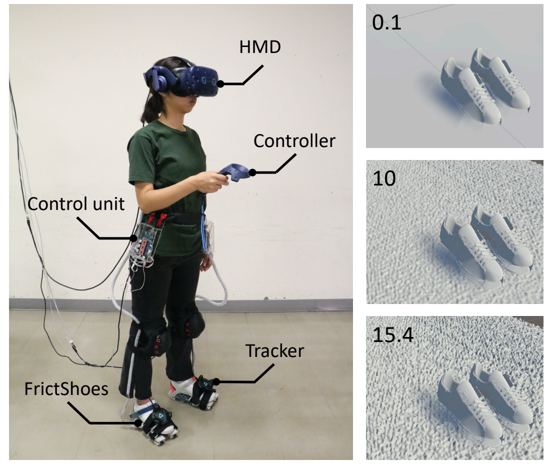

Fig. 7. The setup of magnitude estimation study (left) and ground roughness for minimum, moderate and maximum scale (right).

the device did not move, we progressively increased the motor speed. When the FrictShoe started to move, the force data was recorded and the procedure was repeated several times. By averaging the force data, the maximum static friction force for each level was obtained.

We then calculated the coefficient of static friction ($f = \mu N$) using the measured maximum static friction force and the known FrictShoe weight 1611g, including the force sensor and 1000g weight. The friction force levels (1, 2, 3, 4, 5) have maximum static friction forces of (0.031kg, 0.038kg, 0.227kg, 0.512kg, 1.227kg) and coefficients of static friction as (0.019, 0.024, 0.141, 0.318, 0.762), respectively.

4.3 Task

Based on the previous works [20, 46, 53, 58], the concept of the magnitude estimation study is to render different haptic feedback levels, and ask the participants to adjust the visual feedback scale to best match the perceived haptic feedback. Hence, by mapping the perceived haptic feedback to the visual scale, the perception of haptic feedback is measured or quantified using statistical analyses. For the visual feedback, a white ground was shown in a VR scene and the participants could adjust its roughness. The noise height tool in the Unity terrain API was used to generate a noise field and form a height map for a terrain. The noise terrain height values were randomly assigned from the range between 0 and the current terrain height parameter, which was adjusted by the controller, to achieve appearances of varied of degrees roughness.

4.4 Procedure

The participants wore FrictShoes, held the Vive controller and stood within the VR scene. Before the experiment, each friction force level and the lowest and highest values in the ground roughness scale were presented, so they could have a notion about how to match the visual and haptic feedback. Initially, the terrain height was 0.1, the ground was smooth. As the terrain height was increased using the touchpad on the controller, the ground looked rougher due to the height differences of the noise height map. The visual ground roughness scale range was between 0.1 to 15.4 (Figure 7 (right)), and they could scale up and down by 0.3 scale for the ground roughness scale. The participants perceived friction stimuli on one foot at a time, and the other FrictShoe was set to the maximum friction force level for stably standing. Friction feedback to both feet were examined, separately. They were asked to perceive the feedback when walking in the conventional poses, but they could still use any pose, such as stepping or sliding, to experience friction feedback. They perceived a friction force level and adjusted the ground roughness scale, which in fact was the terrain height parameter, until the visual feedback matched the haptic feedback best. Although directly mapping visual and force feedback was difficult, by gradually adjusting the visual scale, they were able to find the best matching

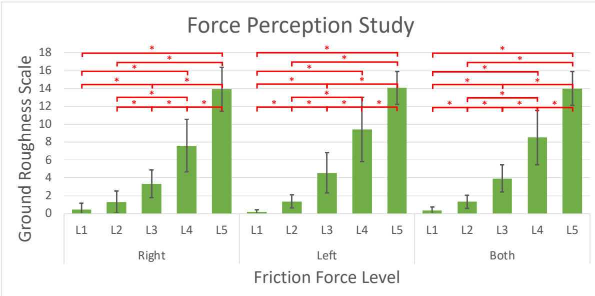

Fig. 8. The results of magnitude estimation study for single left/right foot and both feet. The bars and error bars represent the mean and standard deviation of the ground roughness scale, respectively.

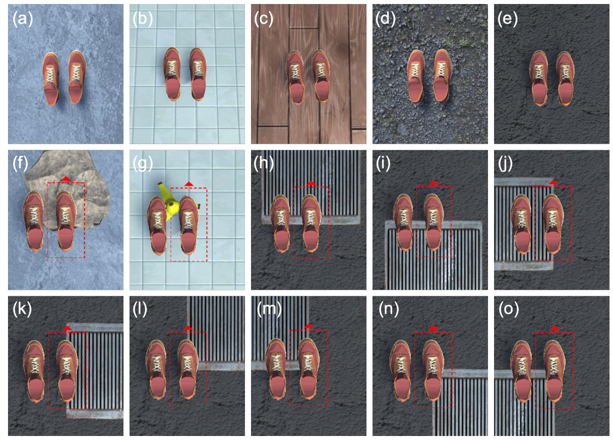

Fig. 9. The 15 conditions of the exploratory study. (a) to (e) are single ground texture conditions, (f) to (h) are multiple ground texture conditions with different object-and-ground pairs, and (h) to (o) are multiple ground texture conditions with stepping onto them with various points of the foot.

scale [35, 41, 46, 58]. After adjusting, they pressed the trigger on the controller to confirm the decision.

A total of 30 (= 2 (feet) × 5 (levels) × 3 (repetitions)) trials were examined by each participant. The order of the feet was counterbalanced and the other factors were randomized. Hence, the independent variables were the foot and level, and the dependent variables were the scales. After the experiment, a brief interview was conducted. The study took about an hour, including the calibration and interview.

4.5 Results and Discussion

The results of the magnitude estimation study are shown in Figure 8. Repeated measures ANOVA and Bonferroni correction were used to statistically analyze the results. Significant effects are found not only for both feet together ($F_{1.97,21.64} = 162.57, p < 0.01$) but also for the single left foot ($F_{2.02,22.25} = 129.36, p < 0.01$) and right foot ($F_{2.10,23.06} = 114.813, p < 0.01$). Post-hoc pairwise tests show that significant differences are revealed among all pairs for both feet together, but among all pairs except between level (1, 2) for the single right foot. Most participants mentioned that levels 1 and 5 are the easiest levels to be distinguished. *P6* and *P10* also said that levels 1, 4 and 5 were easily distinguished. However, 6 participants (*P3*, *P4*, *P5*, *P6*, *P10*, *P11*) supposed that levels 2 and 3 were difficult to distinguish.

In the interview, the participants were encouraged to propose whether the friction feedback from FrictShoes was similar to any friction feedback to the feet they had experienced in their daily lives. *P2*, *P3*, *P7* and *P10* claimed in common that feedback from level 1 was like walking on an ice field or an ice rink. Others commented that the friction force at level 1 was similar to friction forces when walking on a wet tile floor, waxed or dusty wooden floor, or wet floor with water or oil on it. For levels 2 and 3, various scenarios were mentioned, including walking on a dusty PVC court, a gravel road, a smooth tile floor, sand, and mud. Furthermore, *P5*, *P6*, *P7 P9* and *P10* reported that they felt grainy or bumpy feedback like being stuck in a gap or on small stones since the tires on our devices were not perfectly smooth. For levels 4 and 5, walking on a PU running track, a tarred road, a thick-wooled carpet, a bog, a rubber floor, a floor with rubber-soled shoes or in a gym with sneakers were mentioned since the stronger friction force feedback was rendered. *P10*, *P11*, *P12* reported that they felt sticky feedback at levels 4 and 5 which was similar to stepping on chewing gum or flypaper.

Based on the results, we suppose that after removing level 2, the remaining four friction levels are distinguishable. Therefore, the four levels with COFs 0.019, 0.141, 0.318 and 0.762 were chosen. The delays for moving the brakes between friction levels (1, 2), (1, 3) and (1, 4) are 800ms, 910ms and 1090ms, respectively.

5 Exploratory Study

After realizing users' force level distinguishability with their feet in uniform friction patterns in the previous study, we could design varied friction patterns for various ground textures or objects. Since we focus on how the proposed haptic feedback is properly rendered in VR to enhance realism in this VR haptics paper instead of friction recognition ability at varied points on the feet as in perceptual psychology research, we performed this exploratory study rather than a friction pattern recognition study. We explored how users match nonuniform friction patterns with the distinguishable force levels to common VR terrains or ground textures and the conditions when stepping on multiple textures in one foot, *e.g.*, stepping on an object with a partial foot on a ground in this study. The results more or less show users' pattern recognition ability.

5.1 Apparatus and Participants

The same apparatus, including the FrictShoes device, HMD and earbuds, from the previous study was used in this study. 12 participants (8 males) aged 22-32 (mean age: 24.5) were recruited. All of them had VR experience before, and used the larger layout of FrictShoes.

5.2 Task

The participants were asked to adjust the friction force level of each wheel set to best match the presented VR scenarios. Based on the results and comments from the previous study, the four friction levels were used for the adjustment and five commonly mentioned ground textures, including an ice field, tile floor, wooden floor, gravel road and tarred road were used as testing ground textures in this study (Figure 9 (a) to (e)). To be specific, the tile floor was dry, the wooden floor was unwaxed, and the gravel road was fixed without rolling stones.

Furthermore, by presenting the scenarios of stepping on an object with a portion of the foot on the ground in VR, ten conditions for stepping on multiple ground textures with one foot were examined for observing the mappings for nonuniform friction patterns. Three conditions were used to examine the three object-and-ground pairs, including a rock on an ice field, a banana peel on a tile floor and an ditch cover on a tarred road, with the objects in the front portion of the foot (Figure 9 (f) to (h)). We further desired to realize the conditions of stepping on an object with different points of the foot. Hence, by placing the ditch cover on the tarred road for other seven areas on the foot, including rear, inner, outer, outer-front, inner-front, outer-rear, and inner-rear points, we could understand how the participants adjusted friction patterns for an object in total eight points of the foot (Figure 9 (h) to (o)). After the adjustment, we also asked them to rate the satisfaction for their mapping results for each condition.

5.3 Procedure

For each trial, a scenario was shown on the HMD. The participants used the controller to adjust the friction force level of each wheel set of the examined foot on an interface (Figure 10 (left)) in VR. Six white buttons in the layout which were the matched to the wheel sets were on the interface for individual wheel set adjustments. After the participants pointed at and selected a white button using the ray and trigger on the

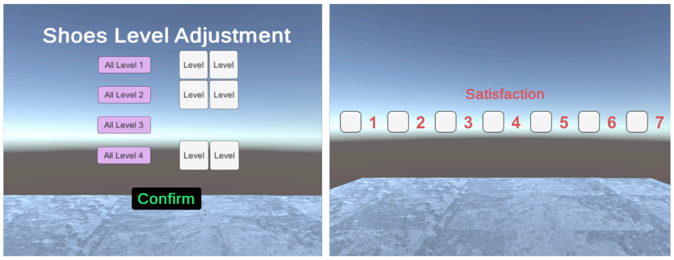

Fig. 10. The friction force level adjustment interface (left) and satisfaction rating interface (right) of the exploratory study.

controller, the selected button turned yellow. They then chose one of the four friction levels by pressing the top or bottom of the touchpad on their controller. After deciding on the level, they pressed the trigger again to change the level of the wheel set. Four pink buttons on the left side were used to adjust all wheel sets to the same corresponding friction level. The participants could repeatedly adjust this until they felt the friction pattern matched the scenario. They are recommended to walk back and forth facing the interface, but they could still use any pose to perceive the friction force feedback in that direction. For the multiple ground texture conditions, they were asked to step on the red dotted rectangle with the examined foot, and adjust the friction force based on what they perceived from that area. After they confirmed the adjustment result by selecting the confirm button, the rating interface for satisfaction on a 7-point Likert scale (Figure 10 (right)) was shown.

A total of 15 conditions were examined. 5 conditions with a single ground texture were randomly examined in the first 5 trials, and the 10 conditions with multiple ground textures were randomly examined in the remaining 10 trials. Only one foot was examined, which was counterbalanced. The FrictShoe on the other foot was set to level 4 for stably standing. After the experiment, an interview was conducted. The study took about one and a half hours, including the calibration.

5.4 Result and Discussion

The mean adjustment results of each condition are illustrated in Figure 11 for a right foot manner. Therefore, the left column is for the inner part and the right column is for the outer part. The results for feedback to the left and right feet are considered symmetrically and averaged. For conditions with a single ground texture, most participants had similar opinions and expectations that the ice field was the slipperiest, followed by the tile floor, wooden floor, gravel road and tarred road. Since the tile was smoother than the unwaxed wooden floor, most of them thought that the friction force of the tile floor was less. For the gravel road and tarred road, 7 of them supposed that the friction force of the tarred road was greater than that of the gravel road.

For the conditions with multiple ground textures, the banana peel was thought to be very slippery (about level 1), the ditch cover was a bit rougher (about level 2) but still slipperier than the tarred road, and the rock was supposed to be very rough (about levels 3 or 4). We found an interesting fact in the condition with the banana peel on the tile floor that the friction force level of the tile floor was greater than that for the tile floor only condition. This might result from the too-small friction difference between the adjacent levels (levels 1 and 2) of a nonuniform pattern on the foot. Therefore, the participants increased the friction level of the tile floor to reinforce the contrast.

For the multiple texture conditions with the ditch cover stepped on using different points of the foot, most participants adjusted the friction level of the whole shoe to that of the tarred road (about level 3 or 4), and then set the corresponding wheel set(s) for stepping on the ditch cover to a lower friction level (about level 2). If they thought stepping on the ditch cover was not slippery enough, they further decreased the levels of the wheel sets nearby, which formed a gradual level change configuration. Furthermore, most participants mentioned that when stepping on the ditch cover with the front or rear portions of their foot, they perceived the largest friction difference between the

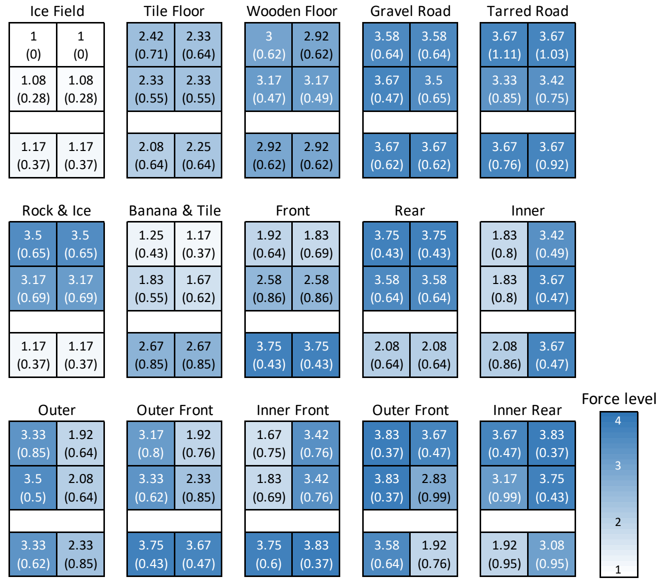

Fig. 11. The adjustment results of the exploratory study. The values are the mean and standard deviation of adjusted friction force levels.

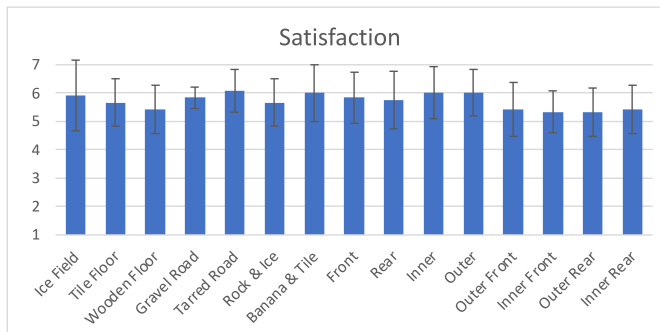

Fig. 12. The exploratory study result. The bars and error bars represent the mean and standard deviation of the satisfaction, respectively.

ditch cover and tarred road, especially with the front. They perceived the larger friction difference from front/rear portions than that from inner/outer portions and further than that in corners.This might be caused by the center of mass transition on the foot during a gait cycle, which allows the friction force for front and rear of the foot to be more easily perceived in different gait phases.

The satisfaction results for each condition are in Figure 12. Overall, the results of all conditions were acceptable by the participants and matching their expectations. For the ground textures with very large or small friction levels, such as the ice field, tarred road, and gravel road, these received relatively higher scores than others. *P4*, *P5*, *P8*, and *P12* felt that it was just like walking on the tarred road, and *P1*, *P4*, *P5*, and *P7* liked the ice field since it was very slippery. For the conditions of the ditch cover stepped on using different portions of the foot, when stepped using half of the foot, it received relatively higher scores than that when stepped with only a smaller portion (a corner) of the foot.

6 VR Experience Study

To observe how multilevel nonuniform friction force feedback affects realism and enhances the experience in VR, we conducted this study.

6.1 Apparatus and Participants

The apparatus was similar to that in the magnitude estimation study. However, the participants were allowed to walk on a 2×2.3m area in

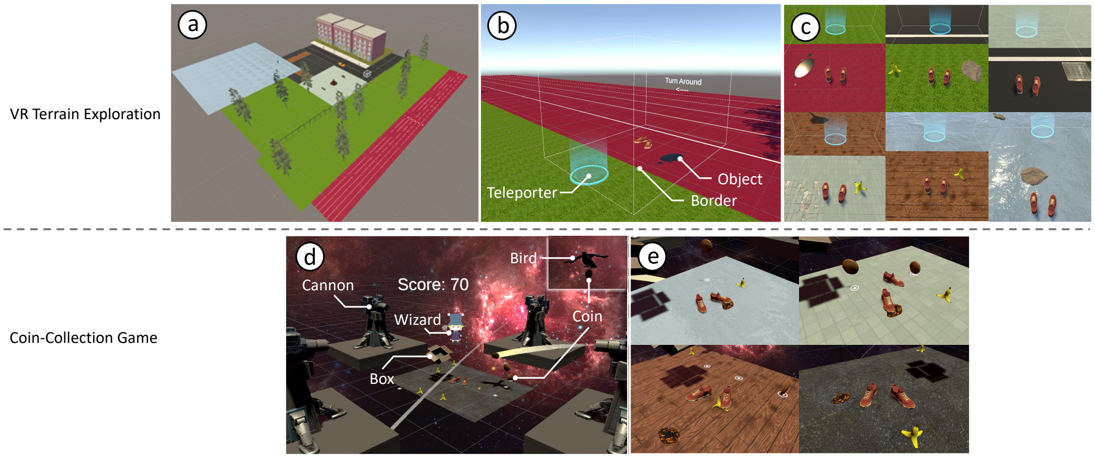

Fig. 13. The scene overview (a), scenarios (b)(c) in the VR terrain exploration. The scene overview (d) and scenarios (e) for the coin-collecting game.

this study, and the game music was played from the headphones of the HMD. 12 participants (2 females) aged 21-25 (mean age: 23.17) were recruited. Two of them had never experienced VR before. Four of them had attended the magnitude estimation study but more than two weeks had elapsed since the prior study, and none of them had attended the exploratory study.

6.2 Task

In this study, we observed how the proposed feedback affects users' experiences in static and dynamic interactions. Therefore, we built two VR scenes, VR terrain exploration (Figure 13 (a) to (c)) and a coin-collecting game (Figure 13 (d)(e)) , for static and dynamic VR interactions, respectively. In the VR terrain exploration, six terrains with different ground textures were presented, including an ice field (level 1), tile floor (level 2), wooden floor (level 3), and tarred road (level 4, but the middle row of the wheel sets were level 3 based on the exploratory study) from the previous study and two new ground textures, a grassland (level 2) and PU running track (level 4). Furthermore, some objects with different textures were placed on the terrains, including puddles of oil (level 1) scattered on the PU running track, rocks (level 4) spread on the grassland and ice field, a ditch cover (level 2) on the tarred road, a broken tile (level 3) on the tile floor, and banana peels (level 1) on the grassland, tile floor, and wooden floor. The six terrains were set in six scenarios, respectively, and three tasks were in each scenario, including the current terrain, objects on the current terrain, and the border between the current and next terrain from the next scenario. The participants experienced all tasks in the current scenario, and walked to a teleporter. After being teleported to a new scenario, they followed an instruction to turn around in a specified direction, which prevented them from being restricted by the wires. Using the teleporter, they could walk back and forth in a limited space in the real world. They experienced the terrains, including the PU running track, grassland, tarred road, tile floor, wooden floor, and ice field, in sequence.

For the coin-collecting game, they held a box and walked across a game field to collect coins dropped by a hovering bird to obtain the score. When a coin was dropped, a bullseye appeared on the ground to show where it would land. The coins bounced on the ground to provide more likelihood to be collected. After a 10-second interval, a wizard randomly switched the ground texture to an ice field (level 1), tile floor (level 2), wooden floor (level 3) or gravel road (level 4). During switching, a 2-second blinking hint was shown to prevent the participants from slipping due to the sudden change. In addition to the ground textures, banana peels (level 1) and lava rocks (level 4) were emitted by four cannons around the game field. These objects provided varied friction levels from the ground textures and hindered them to collect coins. After perceiving all friction feedback from the ground and object textures, they could decide whether to end the game.

6.3 Procedure

Three feedback methods, including visual feedback (V), multilevel uniform friction feedback (U) and multilevel nonuniform friction feedback (N), were compared in this study. The FrictShoes device was worn in all three conditions. (V) provided visual feedback only as a baseline, so all wheels on the FrictShoes were set to level 4 to ensure safety. (U) and (N) are both proposed feedback from FrictShoes in this paper. In fact, (U) is a subset or special case of (N). In (U), if any part of the device stepped on an object, all wheels of it changed to the friction level of the object. In (N), all wheels rendered different friction levels corresponding to the stepped on ground textures or objects.

Based on the exploratory study, we used four bounding boxes at inner-front, inner-rear, outer-front, outer-rear portions of each virtual shoe to detect the textures of stepped on terrains or objects, and proposed guidelines for (N) for each FrictShoe. (1) *Texture detection.* When stepping on the ground, there are three conditions from the bounding boxes for nonuniform feedback, including front-rear, left-right and corner (texture in one bounding box different from the others) types. The friction force levels of the front two and rear two wheel sets in the front-rear type, the left three and right three wheel sets in the left-right type, and the wheel sets in the corner bounding box and the opposite corner wheel set in the corner type are set to the corresponding feedback levels of the detected textures. (2) *Interpolation.* For the other wheel sets in front-rear and corner types, the friction force levels are computed using linear interpolation based on the distances to the wheel sets with the assigned friction levels. (3) *Reinforcement.* When stepping on a ground texture and an object at the same time, which means in a ground-and-object border, and the ground texture and the object are at adjacent levels, then the friction level of the ground texture is adjusted one level to reinforce the level contrast.

A total of 6 (= 2 (VR applications) $\times$ 3 (feedback methods)) conditions were examined by each participant in this study, and the feedback methods were counterbalanced. Since we did not compare between the VR applications, the applications were experienced in sequence. They filled out a questionnaire and rated the realism, enjoyment, preference, and distinguishability after each condition using a 7-point Likert scale which allowed for decimal scores. Distinguishablility means how they felt the ground texture or object they stepped distinguishable from others. Hence, the independent variable was the feedback method and the dependent variables were the subjective scores. After the experiment, an interview was conducted. The study took about one and a half hours.

6.4 Result and Discussion

The VR experience study results are shown in Figure 14. We used a Friedman test (non-parametric alternative to the one-way repeated measures ANOVA) and a Wilcoxon signed-rank test with Bonferroni correction to statistically analyze the results.

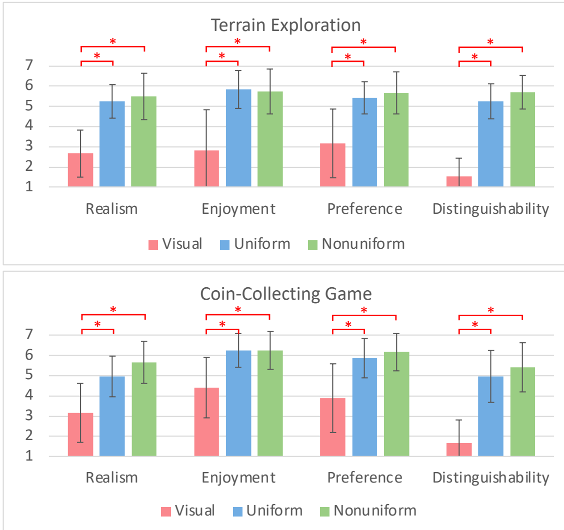

Fig. 14. The VR study results in terms of realism, enjoyment, distinguishability and preference on a 7-point Likert-scale.

For VR terrain exploration, significant main effects are found for all factors, including realism ($\chi^2(2) = 17.15, p < 0.01$), enjoyment ($\chi^2(2) = 14.37, p < 0.01$), preference ($\chi^2(2) = 12.95, p < 0.01$) and distinguishability ($\chi^2(2) = 22.37, p < 0.01$). Post-hoc pairwise tests show that significant differences are found among all pairs except between (U, N) for all factors. For the coin-collecting game, significant effects are revealed for all factors, including realism ($\chi^2(2) = 20.59, p < 0.01$), enjoyment ($\chi^2(2) = 18.24, p < 0.01$), preference ($\chi^2(2) = 20.49, p < 0.01$) and distinguishability ($\chi^2(2) = 16, p < 0.01$). Post-hoc pairwise tests show that significant differences are among all pairs except between (U, N) for all factors.

For the VR terrain exploration, *P6*, *P10*, *P11* and *P12* suggested that the PU running track feedback from (U) and (N) matched their real world experiences. *P3*, *P11* and *P12* felt the feedback from the ice field to be realistic and slippery. *P11* further appreciated the experience when stepping on a rock in the ice field. However, for the feedback of the grassland, tile floor and banana peels, some participants felt too slippery but others thought not slippery enough. Comparing (U) and (N), *P11* and *P12* mentioned that (N) was more realistic than (U), and *P6* and *P8* said that the feedback from (U) did not match the visual feedback. However, *P4* and *P9* suggested that feedback from (U) was better than that from (N) when stepping on an object such as the banana peels since they felt only small friction change in (N). When stepping on an object, the feedback from (U) was like exaggerated or reinforced feedback from (N). Hence, friction change in (U) was more obvious but less realistic. For the reinforcement to adjust the level contrast in the guidelines of (N) for the combinations of tile floor/broken tile floor and tile floor/banana peel, the participants did not notice the tile floor level difference. Furthermore, some of them felt that the friction difference between the tile floor and banana peel was not obvious enough.

For the coin-collecting game, *P1*, *P2*, *P8*, *P9* and *P10* mentioned that they barely perceived the friction differences of the ground textures since they paid too much attention to play the game. They preferred to look up and follow the bird instead of looking down to follow the bullseye to collect coins, which made them easily ignore the ground textures. *P1*, *P5* and *P6* also said that the ground textures and objects changed too fast and frequently to experience the friction feedback. When playing such a dynamic VR game, most participants felt not much difference between (U) and (N). Since no border existed between the ground textures, sometimes the objects were too small or disappeared too fast to perceive in (N). *P2* and *P12* said that the feedback from (U) was more obvious and suitable for rendering objects' textures but *P6* and *P11* supposed the feedback from (N) more realistic. This might explain why no significant difference is found between (U) and (N).

Compared with normal shoes, the FrictShoes device was supposed a bit high, heavy and difficult to bend, which made some participants feel like wearing boots, clogs or getas, which are flips-flops with elevated flat wooden soles. These still more or less affected their walking poses, such as prone to not lifting the feet but dragging or sliding them, and not bending the toes in the toe-off phase of the gait cycle. However, most participants stated that wearing FrictShoes was fairly comfortable and the height and weight of FrictShoes were acceptable. Although our form factor was like roller-skates, they still could walk in conventional poses instead of sliding or rolling the device. Based on the statistic analyses and comments from the participants, we obtained that the feedback from (U) and (N) both proposed by FrictShoes significantly enhance VR experiences. We then summarize some suggestions of using (U) or (N) from FrictShoes. For scenarios requiring feedback with better realism, precision and details, which are usually static applications like VR environment exploration, nonuniform friction feedback is appropriate. For scenarios demanding feedback with better distinction or even exaggeration, which are usually dynamic applications like exciting VR games, uniform friction feedback is more proper.

7 Limitation and Future Work

Although FrictShoes renders varied friction feedback to the feet, there are still some limitations with its current design. Since the device is still a bit heavy, high and hard to bend, more elastic but strong materials could be utilized in future VR shoes devices. To maintain safety, the participants wore knee pads and an experimenter held a cushion spotting them to prevent injury although none of them fell during the experiments. Hence, protective equipment such as knee pads and a hip protector could be used for future safe experiences. Furthermore, to automatically generate corresponding friction feedback for ground textures, the bump map textures of the surfaces could be used for proper mapping in future works. In addition, since the tires and brakes erode over time, calibration is required. This could be improved by sensing the force between each brake and wheel using a force sensor placed between the brake and its shell. Therefore, we could use a PID controller to dynamically adjust the force between the brake and wheel and generate the desired friction force levels. Since the wheels in the current design move in a forward/backward direction, users can not slide with FrictShoes to their left or right to perceive the desired friction feedback. This could be achieved by using omnidirectional wheels with advanced brake design in the future. Although some suggestions for uniform and nonuniform feedback were proposed in the VR study, there is no significant difference between nonuniform and uniform feedback. This more or less limits the nonuniform friction feedback design consideration. In addition, to clearly understand user' recognition ability of friction patterns and the number of independently controlled wheels needed, a pattern recognition study could be conducted in the future.

8 Conclusion

We proposed a wearable device, FrictShoes, to provide multilevel nonuniform friction feedback to the feet to enhance VR experiences. By independently controlling the six brakes on the six wheels, respectively, on each FrictShoe, various friction feedback patterns in uniform and nonuniform are rendered. We conducted a magnitude estimation study to observe how users estimate friction magnitudes and obtained the four distinguishable friction force levels for the feet. An exploratory study was further performed to understand how users map the multilevel nonuniform patterns to several ground textures. Based on the results, we proposed guidelines for adjusting nonuniform friction patterns. Finally, we performed a VR study to verify that uniform and nonuniform friction force feedback from FrictShoes significantly enhance VR experiences in dynamic and static VR interactions, respectively.

Acknowledgement

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