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RealWalk: Haptic Shoes Using Actuated MR Fluid for Walking in VR

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***Abstract*— We present RealWalk, a pair of haptic shoes for HMD-based VR, designed to create realistic sensations of ground surface deformation and texture through MR fluid actuators. RealWalk offers a novel interaction scheme through the physical interaction between the shoes and the ground surfaces while walking in VR. Each shoe consists of two MR fluid actuators, an insole pressure sensor, and a foot position tracker. When a user steps on the ground with the shoes, the two MR fluid actuators are depressed, creating a variety of ground material deformation such as snow, mud, and dry sand by changing its viscosity. We build an interactive VR application and compare RealWalk with vibrotactile-based haptic shoes to investigate its effectiveness. We report that, compared to vibrotactile-haptic shoes, RealWalk provides higher ratings for discrimination, realism, and satisfaction. We also report qualitative user feedback for their experiences.**

I. Introduction

The emergence of advanced stereoscopic head-mounted displays (HMDs), high-end 3D graphics technology, and ultimate cross-platform game engines deliver high-fidelity and immersive VR experiences to users ever. With highly accurate tracking systems, users are demanding more dynamic, whole body activities in a complete, room-scale VR space. Consequently, walking has become one of the most natural interactions for VR.

Providing realistic sensations is demanding to improve the presence and realism of VR. A broad range of haptic devices is used such as gloves [5], [6], [12], vests [10], [7], [11], and suits [17], [1]. Most of them use vibrotactile actuators to replicate simple haptic stimuli, or robotic arms or exoskeleton-type devices to deliver kinesthetic feedback. However, these haptic devices focus on either creating limited haptic cues or delivering force information through expensive and bulky equipment.

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Fig. 1. A screenshot of RealWalk haptic shoes.

A number of researchers also have investigated haptic shoes to provide tactile feedback for walking. Level-Ups [13] are computer-controlled stilts that allow users to experience the elevation in VR. Each Level-Up contains a device worn like a boot and enables the user to walk around the space. Gilded gain [16] is another type of haptic shoes that change the texture of the ground using vibrotactile feedback. Turchet et al. [20] [19] built haptic shoes to simulate real-time auditory and haptic sensations while the user is engaged in walking in VR. They embedded vibrotactile actuators into sandal-like shoes and drove the actuators using audio signals. SoleSound [25] is audio-tactile footwear to deliver underfoot feedback for clinical applications. It uses four force sensors and five actuators to simulate different ground surface interaction using synthesis models. Taclim [4] is commercial haptic shoes that also adopt vibrotactile actuators for VR to provide different textures of the ground surface. HapticWalker [14] is a haptic device that simulates walking experiences. The system consists of two-foot platforms that have 3-DOF per foot. It provides force feedback with 6-DOF force/torque sensors mounted under each foot platform. While these approaches show the feasibility of either texture sensations or ground surface deformation, providing both ground deformation and texture surface haptic rendering still requires more complicated hardware structures.

A number of floor-based haptic displays have been also investigated. Visell et al. [22], [21] created a touch-surface system that can deliver haptic feedback to the user using tiles with force sensors. When a tile is being touched, the values of the force sensor are calculated to detect the touch position and intensity to provide vibrotactile feedback. Blom et al. [3] introduced soundfloor, a new floor-based audio-haptic interface using several transducers for virtual collision feedback. While these approaches show the feasibility of delivering haptic feedback from the floor, it also comes with complicated hardware structures and space requirement.

In this paper, we present RealWalk, a pair of haptic shoes for HMD-based VR, designed to create realistic sensations of textures and ground deformation while users are engaged in walking in VR (see Figure 1). We achieve this by using smart fluid based haptic actuators that are specially designed for this purpose - MR (Magnetorheological) fluid actuators that change its viscosity according to magnetic field inputs. Actuators using MR fluid have been widely studied in different form factors due to their ability of producing high resistive force in a relatively small size including joystick [15], [26], glove [2], [23], touch surface [9], [8], and buttons [24]. With MR fluid actuators, RealWalk naturally delivers both ground deformation and texture sensations, yielding high fidelity walking experiences in VR. This natural design of physical interaction can elicit the feeling of ground deformation while the resistance force can be rendered by controlling the viscosity of MR fluid inside the actuators. We believe that RealWalk shows a novel interaction scheme that adopts the unique property of MR fluid to deliver both ground deformation and texture sensations of the ground surface to provide high fidelity walking experiences in VR.

II. Implementation

A. Design

To design robust and efficient haptic shoes with appropriate locations for MR fluid actuators, we conducted a walking evaluation using insole pressure sensors (MS9713, Kitronyx). The task was to walk naturally in a hallway with 5 m in length (N=6). The insole pressure sensor contained 118 sensing nodes of piezoresistive sensors, with a size of 301.9 mm (length) $\times$ 105.8 mm (width). Each sensor node has a size of 6 mm $\times$ 6 mm and integrated with a spacing of 2 mm in horizontal and 1.1 cm in vertical. The sensors were calibrated with ten levels of the applied force from 1 N to 490 N, and they were embedded in a pair of sandals.

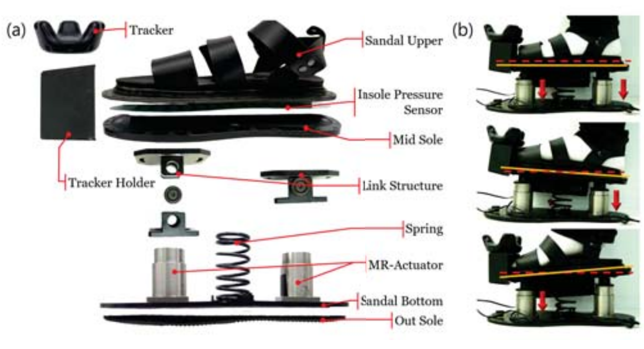

Fig. 2. Structure of RealWalk. (a) Exploded view and (b) Link structure and its motions

The front area was ranged from 1 to 50 cm^2 and the rear area was ranged from 1 to 32 cm^2 in the left foot. The rear area of the right foot has a similar range with the rear area of left foot, 1 cm^2 to 35 cm^2. It is interesting to see that most of the force distributions were centralized in two different regions in the sole: front and rear. Based on the data we collected, we decided to have two MR fluid actuators (each actuator can exert up to 350 N of resistive force) per each shoe with the appropriate positions to place them (upper actuator: 9 cm from top and 6 cm from inner side, lower actuator: 7.5 cm from bottom and 5.5 cm from inner side). During the evaluation, we also obtained interval time between steps to secure the recovery time of the actuators after damping of the actuators.

Figure 2(a) shows the overall structure of RealWalk. It contains a form of sandal shoes with an actuating layer. Two MR fluid actuators are placed to render haptic stimuli onto the frontal and rear parts of a foot, respectively. A spring is installed between two actuators to balance them, supporting the upper sole, and recovering from compression of actuators. We used pivot links to connect the actuators to the upper sole that can tilt up to 3.1°(see Figure 2(b)). It's because there exists unbalanced pressure distribution across the sole and it is required for us to have a more flexible structure of the shoes. This pivot structure allows users to walk more naturally by preventing distortion of actuators from unbalanced pressure between fore- and rear-foot.

B. MR Fluid Actuators

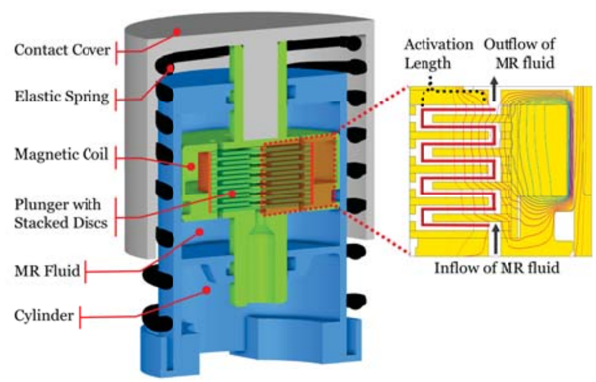

Fig. 3. Cross sectional view of MR fluid actuator that illustrates inflow and outflow of MR fluid.

A key component of physical interaction is MR fluid actuators. MR fluid is a type of smart fluid, and it immediately changes its viscosity when subjected to a magnetic field. We designed the MR fluid actuator to adjust the viscosity of MR fluid by varying the magnetic field intensity based on the type of materials in the virtual ground surface when the actuator is under pressure from a human foot.

Figure 3 shows the cross-sectional view of the proposed MR fluid actuator. In an actuator, several discs are stacked and placed in the center of the plunger, and a magnetic coil is wound around the discs for maximizing the resistive force generated by the MR fluid. In this multi-stacked disc structure, holes are designed to allow the MR fluid to flow in zigzag. When the magnetic coil irradiates magnetic field on

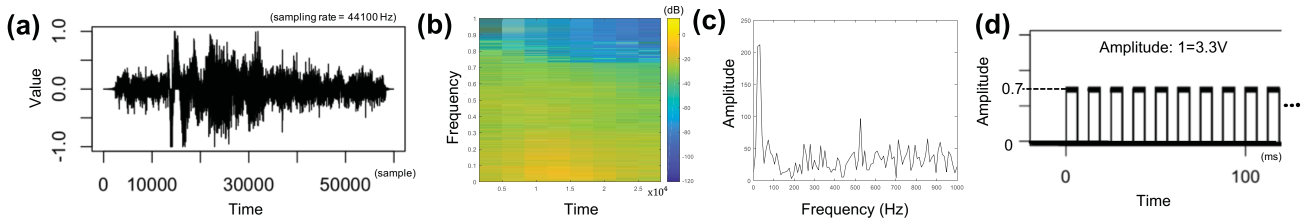

Fig. 4. Haptic rendering process for sand: (a) Original audio signal, (b) Spectrogram, (c) Amplitude spectrum, (d) Haptic feedback signal for MR actuators

the discs, the MR fluid with the increased viscosity passing through the discs is designed to receive the maximum flow resistance by the long flow path (flow mode).

To maximize the resistive force generated by the actuator during the flow mode activation of MR fluid, we performed a series of parametric studies along with FEM simulations. From the simulation results, the radius of the discs was determined as 4.5 mm, and the magnetic flux density irradiated on the discs was designed to be uniform in a radial direction. The maximum magnetic flux density (about 150 mT) irradiated on the discs was formed in the disc of the upper layer, and the minimum value of the magnetic flux density (about 65 mT) was formed in the bottom layer disc. The MR fluid, the plunger with magnetic coils, and multi-stacked discs were together placed in the cylinder. A contact cover was placed over the cylinder with a supporting plate to resist the force from the foot. Ultimately, two MR fluid actuators and one external spring are installed between the shoe and a base sole to complete a RealWalk shoe. The stroke distance of each MR fluid actuator is 10 mm. We confirmed that the recovery time (about 300 ms - obtained using a high-speed camera) of the actuators when the shoe is departed from the land was faster than the same footstep interval (about 550 ms). As discussed in the previous section, the locations of the two installed actuators (front and rear) are determined based on the general foot pressure distribution of human walking. The overall size of the MR fluid actuator determined by the simulation results is 55 mm (length) $\times$ 46 mm (width) $\times$ 50 mm (height). The maximum generated resistive force is approximately 350 N with a power consumption of 2.5 W.

When a user steps on the ground, the two MR fluid actuators are depressed. During this time, a control board delivers a square waveform with appropriate amplitude and frequency based on the type of ground surface and the amount of insole pressure distribution, yielding changes in input current to the magnetic coil. Since MR fluid either increases or decreases its viscosity with respect to the magnetic field derived from the input current, the stiffness of fluid is changed accordingly, delivering a variety of tactile sensations while the actuators are pressed by the foot.

C. Software Structure

The software framework consists of a Unity-based VR application, footstep detection module, and actuator control. Within the VR application, we set the positions of virtual shoes and height of the virtual ground using the tracker information. The VR application is also connected to the control board in RealWalk to communicate with the haptics shoes. The footstep detection is implemented in a two-stage step detection procedure using insole pressure sensors and IR tracker. In this two-stage step detection, we first verify the latest pressure data to check if the foot is landed on the ground or not. If the pressure is greater than a predefined threshold, we then check the current 3D position of the foot in a virtual scene whether its position made contact with the virtual ground. If these requirements are met, the VR application displays the footprint along with appropriate sound (e.g., crunching sound for snow) and delivers the haptic signal parameters to the micro-controller of the shoe via USB interface. Once the micro-controller receives these parameters, a haptic feedback signal is created and delivered to the MR fluid actuators, which in turn generates resistive force. No haptic feedback is delivered if these requirements are not met.

D. Haptic Rendering

1) Natural Delivery of Kinesthetic Haptic Feedback: The unique feature of the MR fluid actuator is that it delivers the sensations of ground deformation by stepping on the actuators using a human foot. Since the actuator is attached under the upper sole and it is naturally pressed when landed on the ground, ground deformation is created with kinesthetic haptic feedback. As all kinesthetic feedback requires the mechanical ground to create force feedback, our design naturally uses the physical ground to create resistive force only when it is being pressed. Since MR fluid can be controlled stably with fast response time (less than 2ms), we can express the resistive force during the footstep with control of viscosity in MR fluid inside the actuator.

2) Haptic Feedback Signals for Ground Materials: For haptic feedback signals, we chose four ground materials of grass, sand, mud, and snow. Since the MR fluid actuators are capable of rendering visco-elastic properties, we designed the new feedback signals of each material that can highlight the features of both kinesthetic feedback of ground deformation and tactile feedback of texture. We achieved this by modulating the amplitude and frequency of square wave signals based on the rendering process using signal transformation. Figure 4 shows the process of making the signal used in

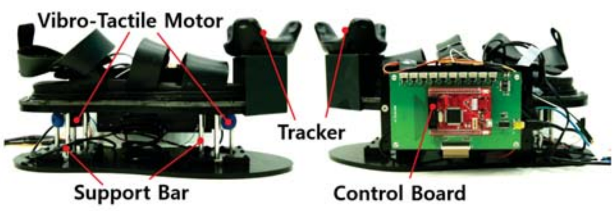

Fig. 5. A vibrotactile-based haptics shoes - VibShoes

our MR fluid actuators for sand material. We first obtained a sound signal source [18] and divided the source into seven time segments (Figure 4(a)). We then obtained the domain frequency by spectrogram (Figure 4(b)). The dominant frequencies were then extracted from each sub-region of the spectrogram plot (Figure 4(c)). The dominant frequency of one signal was then determined by averaging all areas. The final signals are then determined by the extracted dominant frequency with iterative tuning (Figure 4(d)). With the higher amplitude of the signal, MR fluid becomes harder, and the actuator can exert a higher resistive force. On the other hand, the frequency of signal corresponds to the grain size of the ground. By driving the actuators with a higher frequency, we can deliver the sensations like finer grains of the ground material.

For grass with solid feeling, we set the maximum amplitude (3.3 V) with low frequency (under 10 Hz). For sand with grainy feel, we set the 70 percent amplitude with frequency under 100 Hz. For mud with smooth and muddy feeling, we initially set the maximum amplitude then gradually decrease to minimum amplitude. For snow with crispy feel, we designed a superimposed signal with the 80 percent amplitude with higher frequency and minimum amplitude with low frequency.

III. Evaluation

One of the main contributions of this work is to deliver both ground deformation and texture sensations with different materials using smart fluid in a VR application. In this section, we report a user study conducted to investigate the effects of RealWalk by comparing it with one that adopts conventional vibrotactile haptic actuators (we call this *VibShoes*). As an experimental VR application, we implemented four different VR scenes with ground materials: grass in Spring, sand in Summer, mud in Fall, and snow in Winter.

A. Participants

Twelve participants (6 females, mean age = 28.1 (SD=2.15), mean foot size = 250.0 mm) were recruited to participate this experiment and received $6 coffee coupons for their participation.

B. Experimental Setup

We prepared two pairs of haptic shoes for this experiment: RealWalk (with MR fluid actuators) and VibShoes (with vibrotactile actuators, see Figure 5). Both RealWalk and VibShoes have the same base structure (i.e. sandal type with links) and a control board. To generate vibration feedback, VibShoes uses the same number of two vibrotactile actuators (Tactile Labs Haptuators BM3C) at the same position as MR actuators. It also used a number of supporting bars to keep its height as same as RealWalk. The rest of the hardware components were identical between two types of haptics shoes (insole pressure sensors, trackers, links, etc). VibShoes used original audio signals from [18] whereas RealWalk used the haptic feedback signal through the process of using spectrogram and FFT (see Figure 4).

Fig. 6. Experimental setup: (Left) a person with HMD headset, headphone, and RealWalk, (Right) VR scenes of four seasons

A VR application was built using Unity with C# scripts for this user study. It runs on our main windows PC (CPU: Intel Xeon E5-v3, RAM: 32 GB, GPU: Nvidia GTX 980 Ti). The shoes were connected to the application and communicated via USB. We used HTC VIVE for a wearable visual display and tracking the head and shoes. A VR room was built by diagonally placing two base stations for tracking in a 4 m $\times$ 4 m space. Each base station was placed at 2 m height and tilted 45°toward the ground.

Figure 6 shows a participant (left) and VR scenes (right) for this experiment. In a spring scene, the grass was covered on the ground to provide the characteristics of grass material (grass). In a summer scene, users were allowed to walk around the beach sand (sand). In a fall scene, the ground was covered with mud materials inside the woods (mud). Lastly, a winter scene was implemented with snow piled up on the ground (snow). In all four seasons, users were allowed to freely walk around the scenes while wearing HMD and haptic shoes (RealWalk and VibShoes), perceiving different sensations of material deformation of the ground surfaces. All participants listened to pink noise from a headphone to block any auditory cues from the experimental apparatus.

C. Procedure

In each session, participants were asked to wear the HMD headset and put on either RealWalk or VibShoes in random order (see Fig.6). We also asked them to wear headphones to play pink noise and eliminate any other noises. Prior to the main experiment, we asked participants to freely wear each type of shoes and walk around until they get familiarized with the devices. In the main experiment, the task was to walk around each of four scenes with haptic shoes. The user was placed in one of the virtual scenes and asked to walk around the scene for one minute. We asked them to walk as natural as possible with normal walking speed. Once the participant completed the task with either RealWalk or VibShoes, he/she was then asked to wear another pair of shoes to explore the same scenes (each scene with one minute). We allowed participants to spend more time on the task if necessary. After completing a session, a questionnaire sheet was provided to measure the participants' responses on their walk experiences: *Sensation* - Sensation from the shoes are appropriate with the ground surface (i.e. Grass, Sand, Mud, or Snow). After completing all four sessions, participants were also asked to rate their overall experiences with following questions: *Satisfaction* - I was satisfied with the shoes; *Discrimination* - I was able to distinguish the four different ground surfaces; and *Realism* - My walking experiences was realistic. They were asked to respond to each question by marking on a horizontal line using a visual analog scale with a label on each end: 'Strongly Disagree' and 'Strongly Agree'. They were also debriefed regarding their walk experiences in VR after completing all sessions.

IV. Results

We averaged all participants' *Sensations* score (0: strongly negative, 100: strongly positive) for each of the four scenes and represented them in Figure 7. The averaged scores of RealWalk were higher than those of VibShoes for all scenes. We found statistical significance of the two main factors: haptic shoes ($F(1, 11) = 25.81, p < 0.001$) and VR scenes ($F(3, 33) = 12.48, p < 0.001$) via a within-subjects two-way ANOVA. Simple effect analysis for the four different grounds revealed statistical significance only for Mud ($p = 0.013$). As observed in Figure 7, RealWalk with Snow scored the highest (71%) among all combinations.

It is also interesting to note that VibShoes with Mud scored the lowest among all combinations. It is probably due to the fact that Mud does not contain distinct texture and thus cannot be easily replicated with vibrotactile cues. On the other hand, RealWalk scored significantly higher than VibShoes (although the score was around 50%), showing feasibility of replicating the sensation of ground surface like mud with high viscosity. This can be due to the fact that MR fluid actuators may create smooth deformation of mud during their stroke time.

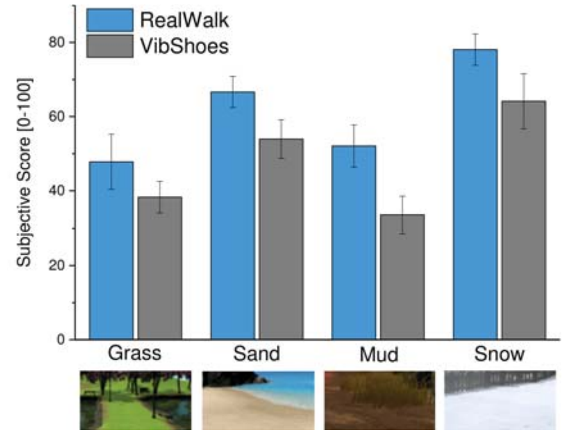

Fig. 7. Mean subjective ratings of haptic feedback for each of the four scenes. Error bars represent standard errors.

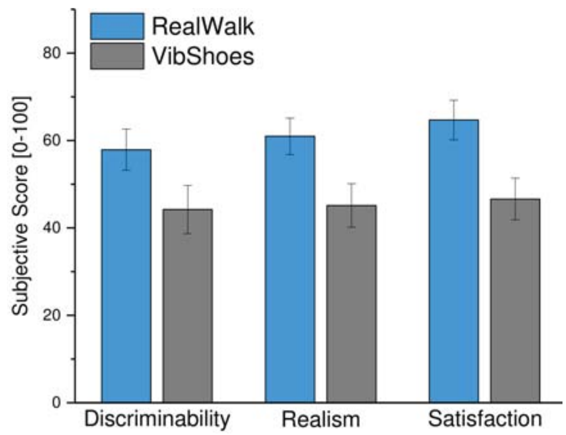

Fig. 8. Mean subjective ratings of haptic feedback over the four scenes by measures. Error bars represent standard errors.

We also compared the scores from both RealWalk and VibShoes for the three overall measures: Discrimination, Realism, and Satisfaction (see Figure 8). Participants reported that, compared to VibShoes, they were able to distinguish the four different ground surfaces (Discrimination), their walking experiences was realistic (Realism), and they were satisfied with the shoes (Satisfaction) with RealWalk. The differences were statistically significant over all three measures ($p = 0.019$ for Discrimination, $p = 0.013$ for Realism, and $p = 0.021$ for Satisfaction). The results from these subjective measures show that RealWalk can create more distinctive and satisfying ground surface sensations with higher user satisfaction than the conventional haptic shoes.

V. Discussion and Conclusion

We presented RealWalk, a pair of haptic shoes that create realistic sensations with both kinesthetic feedback of ground deformation and tactile feedback of texture sensations through physical interaction in a natural way using human footstep force on MR fluid actuator. With MR fluid, realistic sensations of different types of ground materials can be delivered since its state can be changed rapidly from liquid to solid by forming the magnetic particles into a chain. We implemented and integrated both hardware and software modules for RealWalk including MR fluid actuators, insole pressure sensors and foot detection, and haptic rendering. We also introduced four different virtual scenes of the four seasons to conduct the user study and provide a design space for an interaction scenario.

Through the user study, we noticed that RealWalk received higher overall scores compared to VibShoes. RealWalk received almost 80% scores for Snow and also higher scores in Grass, Sand, and Mud. A number of participants (P2, P5, P6, P7, P10, P11, P12) reported very positive responses on experiences with RealWalk. P5 reported that "feeling was so real for sand and snow because my feet were pushing down to the ground." P8 gave us a comment that "I felt a sense of depth when I stepped on the ground and felt the ground more clearly." P10 also reported that "I felt the subtle ground and my feet were more sensitive than I thought." These participants reported that they felt more realistic ground deformation than that of VibShoes since they can feel the depth and viscosity of the ground. Results also revealed that participants were more satisfied, able to distinguish four different ground surfaces, and their experience was more real with RealWalk.

Nevertheless, there's room for improvement in actuator design and haptic rendering. Since we designed our actuators to allow enough foot depress for a footstep, we used low-carbon steel made cylinders for actuator housing to generate strong resistive force in a flow mode, yielding tall (72 mm) and heavy structure (450 g). We are aware of this limitation that it is not proper for long-term use. This limitation can be improved by applying the most energy efficient squeeze mode of the MR fluid. Pre-defined haptic signal profiles based on trial-and-error approach with different amplitudes and frequencies can be further enhanced by adopting more scientific methods such as data-driven haptic rendering to deliver more realistic sensations to the users. The foot pressure data can also be used to provide different parts of the sole such as front and rear in the near future.

We believe that our design of RealWalk shows the feasibility of applying smart fluid in VR and opens up a wide range of possibilities in a wide range of interactive VR applications. Through the design and implementation of RealWalk, we also showed the natural delivery of ground deformation sensation through physical interaction between the shoes and the ground. Future work will extend the present study by considering the issues that we mentioned above to deliver more realistic and natural walking experiences to the users.

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