Push-Ups: Enhancing Kinesthetic Experience with Shape-Forming Devices on the Feet Soles

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ABSTRACT

This paper explores directional kinesthetic force feedback on feet for enhancing foot-related experiences in virtual reality. We present *Push-Ups*, a pair of pneumatic shoes capable of outputting motions to users' feet soles via the shape-forming shoe bases, to enhance users' kinesthetic experience in a virtual ski. Each *Push-Ups* shoe comprises four pneumatic muscles in the base, allowing to present ten shape patterns and thus ten different motion outputs. Our first study validated the effectiveness of the motion output through a recognition study. The second study evaluated the user experience of the system on a virtual ski experience, which demonstrated that users perceived higher enjoyment and realism with the kinesthetic force feedback provided by *Push-Ups*.

CCS CONCEPTS

• **Human-centered computing → Systems and tools for interaction design**.

KEYWORDS

Shape-forming interface; kinesthetic force feedback; haptic shoes; virtual reality

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Figure 1: The Push-Ups system outputs kinesthetic force feedback on the user's foot with a shape-forming shape base. Here, a push-up at the fore sole.

1 INTRODUCTION

Kinesthetics refers to the perception of being in motion and sensing the movement of limbs [15]. Kinesthetic force feedback is then a simulated haptics devoted to modulate the perception, as it is known as an effective augmentation for enhancing simulated sport activities in virtual reality (VR). The basic mechanism is to drive physical movement on the users' body, which is to be matched with visual kinesthetic users' perception of a sport event. This output motion on a body serves as a cuing for a visual kinesthetics [18], not necessarily replicating the corresponding physical kinesthetics. Timely and properly located feedback on users can increase user immersion and realism and has reported beneficial to reducing motion sickness [31] in locomotive activities in VR. Each different activity needs dedicated feedback design, thus device, to produce proper feedback, like motion platforms made for simulated inertial force in a car-racing experience. More recent research has focused on producing kinesthetic force feedback on users' hands [10, 18, 19] to fulfill a wide range of activities while preserving user mobility during interaction.

This work focuses on simulating an up-pushing kinesthetic force feedback on the user's feet from the foot sole. The technical challenge we face is producing a kinesthetic output that goes against the user's weight to make a motion to the body. For such scale of force needed, large-scale motion platforms were often used but would obscure user mobility. Previous attempts proposed motion output devices [23][24] that can be attached on the shoe bases, which permit a degree of mobility but also had to add substantial weight to users' feet, negatively impacting user experience.

We propose *Push-Ups*, a pair of lightweight pneumatic shape-forming shoes, of which changes in the shape of the shoe bases are transformed into kinesthetic output on the wearing feet. In other words, the user is actuated by the shoe base. To enable shape forming, each shoe is affixed with four pneumatic muscles [4], or air muscles, arranged in the shape of a diamond on the base. This particular arrangement allows two-dimensional motion outputs acting on the foot sole, resulting in a range of push-up motions from the ground. As demonstrated in Figure 1, the shoe device pops up on the fore base, generating a push-up on the fore sole.

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Pneumatic muscle systems share a unique trait that the power supply, usually an air compressor, and the control valves can be placed away from the end actuators (e.g., the shoe base), minimizing additional loads to the user. *Push-Ups* is benefited from pneumatic muscles for their strength and a short reaction time, allowing interactive shape update. The lightness of the muscles supports user mobility, although users are still constrained by the range of pipes connecting the air source to the shoe bases. The shape-forming feature of *Push-Ups* benefits a range of applications that seek to directly act on users' feet, such as experiencing skiing activities in VR.

The main contribution of this work is the design of shape-changing shoe bases that allow to produce directional kinesthetic force feedback from the bottom of the user's feet. We further contributed an implementation based on pneumatic muscles, an experiment demonstrating its effective shape output, and a user study on a ski experience enhanced with kinesthetic force feedback on feet.

2 RELATED WORK

We review related works on haptic output on feet and pneumatic interfaces for haptic interaction.

2.1 Shape-Forming Interface on Feet Sole

Locomotion had been a focus of simulated haptics at feet with goals of letting users walk indefinitely while keeping them in place, enabled with active floors [11] or wheeled shoes [12]. More recent researches proposed simulating surface terrain with the idea of shape forming shoes. Considering the gesture of feet when stepping on slopes or edge of bumps, deliberately tilting the user's palm forms illusion of standing on an uneven surface. This can be achieved by shoe bases embedded with active air chambers [28] or wooden flaps [8] that implement the shape-forming mechanism. In addition to locomotion, Sasagawa et. al. explored the shaping-changing shoe soles using jamming [22] to alter the insole condition, leading to change the user's foot activity. Inflashoe [2] studied inflatable shoe sole to dynamically enhance comfort of footwear.

Similarly, shape-forming shoes also exploited to simulate stepping on stairs by expanding the height of shoe bases. Schmidt et al. [23] mounted a lift platform on the shoe base allowing it to suggest a dynamic height off the ground on which the user steps on. Balloon Shoes [16] simulated the height through expanding and shrinking non-elastic air balloons attached on the shoe base. To avoid the driving mechanism needing to work against user weight, which would require high-power actuation, the above shoe interfaces tacitly implemented the formation of shape during the shoe being off the ground. In other words, they can not produce active feedback that pushes the user's feet to move.

Using pneumatic actuation, Push-Ups distances the power mechanism from the end actuators mounted on shoe base. This effectively reduced the weight of the wearable device, and still preserved the power and strength traditionally achievable only by heavy motors. This allows Push-Ups to implement terrain changes when users' feet stay on the ground such as at skiing.

2.2 Pneumatic Interfaces for Haptic Interaction in VR

Pneumatic interfaces have been extensively explored for the study of shape-changing interaction in HCI for tangible [9, 27, 30] and wearable [25] haptic interfaces. Here, we focus on pneumatic interfaces which were tasked with providing haptic feedback in virtual reality. Frozen Suit [1] proposed jamming the user's joints pneumatically to constrain the joints' movement. ForceJacket [7] integrated an array of pneumatic airbags in a jacket for producing normal forces across the body. HangerOVER [17] embedded airbags in a constrained headband to intrigue hanger reflect effect. Pneumatic muscles were incorporated into gloves and suits for delivering force feedback at hands [5] and arms [6]. PuPoP [25] explored the application of pneumatic airbags serving as wearable props in VR. TilePop [26] extended the concept with an array of pneumatic floor tiles that pop up for body-scale props in VR.

The previous works incorporated pneumatic interfaces for acting haptic feedbacks on the users or as haptic props in VR. In this work, the Push-Ups is tasked with delivering haptic feedback to the feet soles. We use pneumatic muscles attaching to the shoe base as props that push up the feet for kinesthetic force feedback.

3 THE PUSH-UPS SYSTEM

Push-Ups aims to generate kinesthetic force feedback from the feet soles. We enable this by implementing a pneumatic shape-forming interface on the shoe base. An pneumatic muscle, resembling the work of a human muscle, consists of an inflatable inner tube inside a braided mesh, clamped at the ends. When the inner tube is pressurized and expands, the geometry of the mesh acts like a scissor linkage and translates this radial expansion into linear contraction. Typically, pneumatic muscles are used as linear actuators. In this work, we laid the muscles on a shoe bottom and used their radial expansions for shape formation.

Figure 2 illustrates three possible designs we tested to produce two-dimensional kinesthetic output. We determined on the final design (Figure 2a), suggesting four muscles arranged in the shape of a diamond affixed on a shoe base, because 1) it avoids overlapping muscles as in Figure 2b, which caused doubled actuations at the interaction points, and 2) it excels at more detailed direction outputs than the design of Figure 2c. Figure 3 shows 10 shapes afforded by the diamond design, where the parts colored in blue indicate the muscles of inflation. This includes shapes to prompt the foot to be tilted in one of the eight directions, be lifted off the ground, and released to the ground.

3.1 Implementing the layout

While implementing the layout on shoe bases seems straightforward, we have encountered into several design challenges resolved through several iterations, owing to the characteristics of air muscles, to attain effective results.

3.1.1 Keep the clampers outside of the shoe base. The ends of muscles are tightened with a clamper and capped with a 3D-printed plug (Figure 4). These components can interfere in the actual actuation and act as undesired hard bumps when stepping. Since inflation shrinks a muscle in length, which pulls the clampers to

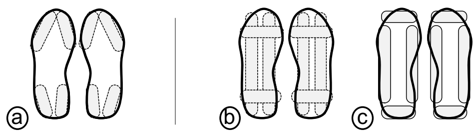

Figure 2: Layouts of air muscles we have visited and determined on the design-(a) for the even elevation over the design-(b), and more detailed direction cues over the design-(c).

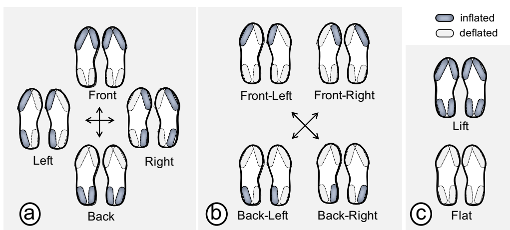

Figure 3: The ten shape-forming patterns Push-Ups affords. Their kinesthetic output can (a)(b) tilt the users' feet into one of the eight directions, (c) lift the feet off and release back the ground. Inflated air muscles are colored in blue.

the shoe base, the muscles should be long enough such that the clampers would be staying outside the range of the shoe sole after shortening. Our design used two 20-cm muscles in the fore sole, as well as two 18-cm muscles in the rear, matching with the actual shoe size.

3.1.2 Affix muscles in place. The muscles need to remain at the designated locations on the shoe base to ensure the shape formation. However, shrinking of a muscle in length came with its strength on inflation, which makes it tricky to define a firm attachment. Hard coupling of a muscle on the shoe base can tear open the shoe at the attachment point on actuation due to the strength in shrinking. As shown in Figure 4, we implemented elastic coupling of a muscle to the shoe by connecting its two ends and the body onto the shoe base with elastic bands. As such, a muscle's 3D-printed plugs contain hooks for building the linkages. For each muscle, we created four openings, each fitted with a plastic pipe that holds the opening, at designated locations on the shoe base for the attachment of four bands. As a result, the elastic bands can keep muscles in place no matter the shape changes on inflation and deflation.

3.1.3 Smooth the top of shoe base. All these openings and passings of elastic bands created some subtle bumps on the shoe sole, which we found to be undesirable. Thus, we covered the shoe soles with a pair of insoles to ensure a comfortable feel of foot touch.

3.2 The pneumatic system

Figure 5 illustrates a diagram of the pneumatic system. We connected eight muscles on the shoes with air pipes to the air source long enough to suggest a walking area of two meters in diameter. Each air pipe beyond the walking area is split into two pathways for inserting and releasing air, each controlled through an electric binary valve (EVI7/9, DC 12V, 6.5 W). There were eight binary valves for inserting air into each of the eight muscles to one of the two proportional valves (CKDEVD-1900) depending on which shoe base it served. The proportional valves, which have a built-in air-pressure sensor for closed-loop control, allow the operation of the valve by a target air pressure. Through proportional valves, the air compressor (PUMA MA112A, AC110V, 1.5HP, 8 kg/cm2), which can generate up to 785 KPa, fed air flows into the muscles on each shoe. The other eight binary valves for releasing air were left open-ended. The 16 binary valves were connected to a 16-relay module controlled by an Arduino Mega 2560 running on a Windows 10 Intel i7-7700K computer equipped a GTX1080 card. The proportional valves, also connected to the Arduino, can adjust the output pressure by feeding it a 0-5 V DC signal. The same computer also served VR applications implemented with a Unity 3D engine.

With the binary valves, the actuation of muscles and the shape formation in each shoe can be individually activated. Further, by grouping muscles into separate proportional values for each shoe, we gain the ability to produce a different force level or force modulation on each muscle group.

3.3 Parameters relating to the interface

Considering that the pneumatic muscles could be fully inflated before reaching the compressor's maximum pressure, as well as for safety reasons, we set the maximum input pressure to muscles at 160 kPa, controlled by the proportional valves. Operating with this pressure, each shoe is estimated to afford up to 154.4 kg in its maximum load. However, since feet bear a force of approximately five times body weight during a stance in normal walking, and up to 13 times during activities such as running [3], we targeted the *Push-Ups* prototype for applications of standing types of activities, for which we introduced ski for the demonstration.

We measured the following parameters of *Push-Ups* in use. The height change of shoe sole from the ground is about 12 mm. The inclining angles for forward, backward, left, and right tilting are 3.53, 5.15, 7.89, and 7.12 degrees, respectively, as indicated in Figure 6. The reaction time to complete the lift pattern from the flat pattern against normal human weight in a standing condition was measured at 1.18 s. Each shoe included muscles that weighed about 500g.

4 PUSH-UPS: EXPERIENCING VR SKI

We demonstrated *Push-Ups* with a ski experience. In this experience, the user wearing Push-Ups crouches down a bit and holds the two ski poles in his or her hands. As shown in Figure 7a, we made the ski poles with a T-shaped top as a handle connecting to a sucking disc stuck to the ground beside the user's feet. In this way, the poles work as levers, which suggest a degree of motion for the ski poles and also serve as supports when users lose balance. Our initial implementation adapted the poles for direction control by attaching them with VIVE trackers. The user control was removed in the final experience in order to deliver consistent ski experience across users no matter their skiing skills.

The experience consisted of a preprogrammed route in the ski run. Once started, the experience unrolled itself no matter the user's

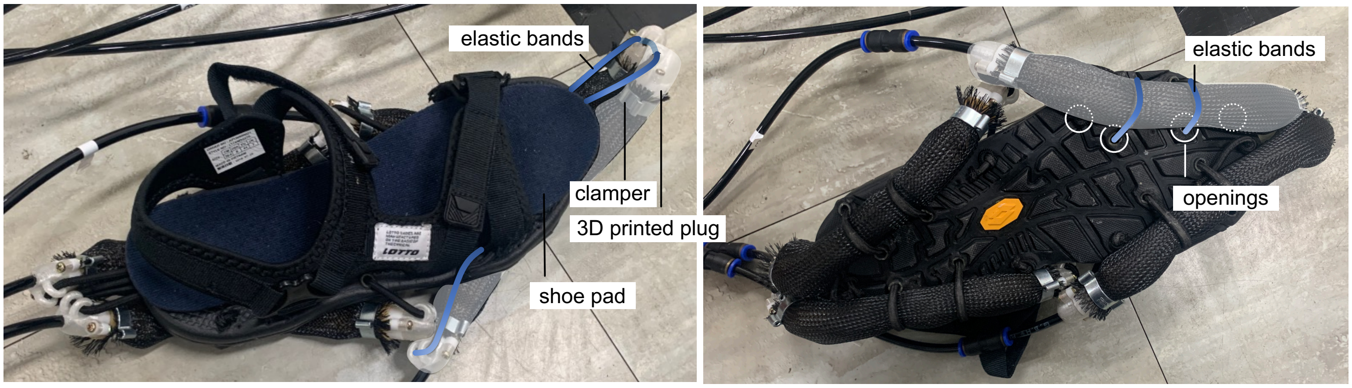

Figure 4: The design of the Push-Ups shoe: (a) a front view of the right foot and (b) a bottom view.

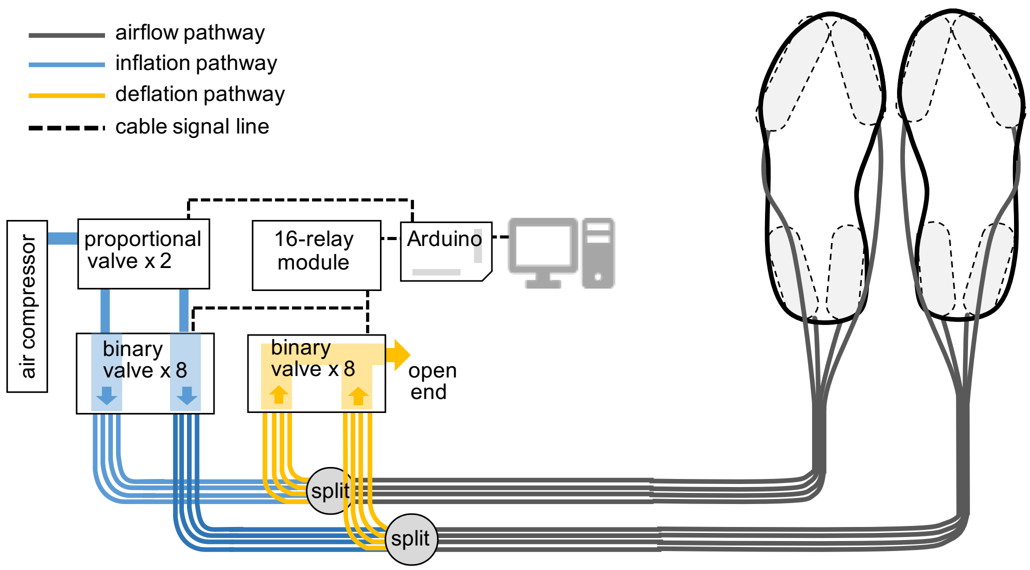

Figure 5: The diagram of the control and pneumatic systems. The blue line indicates the inflation pathway, the yellow the deflation pathway, and the dark the pathway for both. The dashed line indicates the control signal line.

action. In other words, the user would shadow the experience as if he or she was actively acting it out. To assist the shadowing, the route is highlighted in such a way that the user understands what actions are required to act accordingly (Figure 7)b-g. In the meantime, *Push-Ups* generates kinesthetic force feedback on feet in response to various events on the ski run, including racing down steep slopes, making left and right turns, jumping off ramps, etc.

On speeding when facing a slope, we push up on the rear part of the shoe (Figure 7b). On braking, such as when taking a turn, we push up on the side of the shoe opposing the turning direction to simulate snow stacking under the ski. When taking a left turn, for example, the front-right corners of shoes are inflated, indicating the start of a turn (Figure 7c); then the right half of the soles lifts at the turning point (Figure 7d); followed with the shoes being flatten on completing the turn. On taking a ramp, *Push-Ups* lifts the front half to reflect the upslope underneath the ski (Figure 7e). On jumping off the ramp, all pneumatic muscles deflate (Figure 7f). On landing, we invoked a short inflation (0.75 second) at the moment the ski touches the ground. Finally, a parallel stop to the left before the finish line involves a right-half lift (Figure 7g).

5 STUDY 1: SHAPE PATTERNS RECOGNITION

We conducted a shape-recognition study to investigate the effective shape forming of the *Push-Ups* device. After briefing the study, participants put on the Push-Ups shoes. A pair of noise-canceling earbuds (Sony WI-1000X) and the Vive Pro head-mounted display were given to the participants and worn. We gave the participants two Vive controllers to proceed responses during study. In the experience session, all patterns in Figure 3 were presented once on both shoe bases with answer. In the formal session, a trail contained

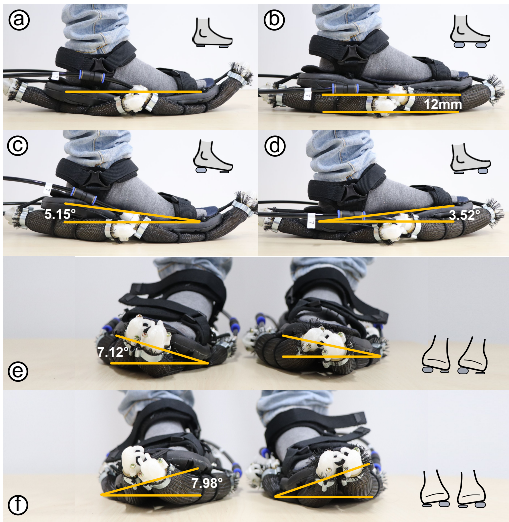

Figure 6: The forming shapes on the shoe bases prompts the user's feet from the flat condition for up-lifting (pushing on all), forward / backward tilting (pushing on the fore and rear sole), lateral tilting (pushing on the sides).

patterns randomly selected for each shoe, where the patterns were actuated simultaneously, lasted for three seconds, and returned to the flat condition. Then, participants had to input the recognized pattern for two shoes with the two hand controllers, respectively. There were 99 (=10x10-1) combinations of 10 patterns across two shoes, excluding the case in which both patterns were *flat*. With three repetitions, each participant experienced 297 trials in total. There were 5-minute breaks between two combination sets. The study took 60 minutes for each participant. We recruited 12 participants (five females) between 20 and 24 years old (M = 22.45 *year;* SD = 1.51) with an average BMI of 21.93 (SD = 3.45) and average weight of 61.75 (SD = 9.13).

5.1 Results and discussion

Figure 8 displays the recognition rates of each foot. Participants could effectively identify the forming shapes. The averaged recognition rate was 95%. We conducted a two-way repeated-measures ANOVA analysis on the two factors *Foot* (left and right) and *Pattern* (the 10 patterns). The assumption of sphericity was met, and the results revealed a significant main effect for *Pattern* ($F_{9,\,99}$ = 2.537, p<.05) but not for *Foot*. There was no interaction effect between *Foot* and *Pattern* (p>.5). This implies that there is no difference in the recognition between two feet. To gain further insight, we merged data across two feet and produced a confusion matrix of shape patterns in Figure 9.

Looking into the recognition rates, the left (91.5%) and right (92.9%) patterns appeared lower than other patterns (M = 95.78%, SD = 2.07). We speculate this is to do with the biomechanisms of the ankle, where the overall range of motion in the frontal plane (inversion-eversion) corresponding to left-right titling is narrower than that in the sagittal plane (plantar-dorsiflexion) to front-back titling [3]. Moreover, participants were more likely to misidentify them as nearby patterns, such as *right* regarded *back-right* (4.9%) in the right foot, and *left* regarded *front-left* (5.4%) in the left foot.

6 STUDY 2: USER EXPERIENCE

To validate the design, we conducted a simple user study. We recruited 12 participants aged between 20 and 34 (M = 24.17 *year,* SD = 3.41). All participants had experienced VR. None of them had seen the device beforehand. Participants experienced the ski experience with and without the feedback provided by *Push-Ups*. The experience lasted 50 seconds and contained three left turns, two right turns, and two ramp jumps. We collected their ratings on realism and enjoyment using a 7-point Likert Scale (1: strongly disagree; 7: strongly agree), as well as measures of motion sickness with the Sickness Questionnaire (SSQ) [13] before and after each experience. The order of experiences across participants was counterbalanced. A 10-minute break was required between experiences. The study was completed with an open-ended interview. Then, the participant was rewarded with a small compensation. The study took 30-40 minutes in total.

6.1 Results and Discussion

Figure 10 shows the results of user ratings on realism and enjoyment, as well as the SSQ difference, for Push-Ups and Baseline (without force feedback). Wilcoxon signed-rank tests found that the realism rank in the Push-Ups condition (M=5.25, SD=0.86) was significantly higher than that in the Baseline condition (M=3.0, SD=1.04) ($Z = -3.205$, p<.05) and that the enjoyment rank in the Push-Ups condition (M=5.75, SD=0.75) was also significantly higher than that in the Baseline condition (M=3.0, SD=1.41) ($Z = -3.075$, p<.05).

A pairwise t-test on SSQ difference found a significant difference between Baseline and Push-Ups conditions (($t(11)$ = 0.967, p<.5)). However, the relatively high scores of SSQ differences indicated that participants generally are subject to some level of motion sickness no matter the haptic feedback. We consider this might be due to the high vection of the ski experience that set the high sickness at default. Nonetheless, this also implied that solely the motion output on feet is not sufficient to counter motion sickness at this level, where multifaceted feedbacks that involve a wider range of the body should be accounted for.

During the interview, all participants reported they noticed and enjoyed the force feedback delivered by the *Push-Ups* device. They described the tilt they experienced when a left or right turn was made, as well as the height change they felt when jumping off ramps. For most of the participants, the power generated with our device is sufficient to enhance the skiing experience. One of the participants stated, "I felt a strong pushing force that moved my center of body weight to another direction."

As mentioned, the participants also appreciated the game when it came with *Push-Ups*. Not only did we receive significantly high ratings on the experience's realism and enjoyment but a participant even quoted, "The game (skiing experience) was so realistic and enjoyable that even after I took off the HMD, I feel like I'm still in the game." Another said, "Even though I knew I didn't have control over the direction and speed of skiing, with the feeling beneath my

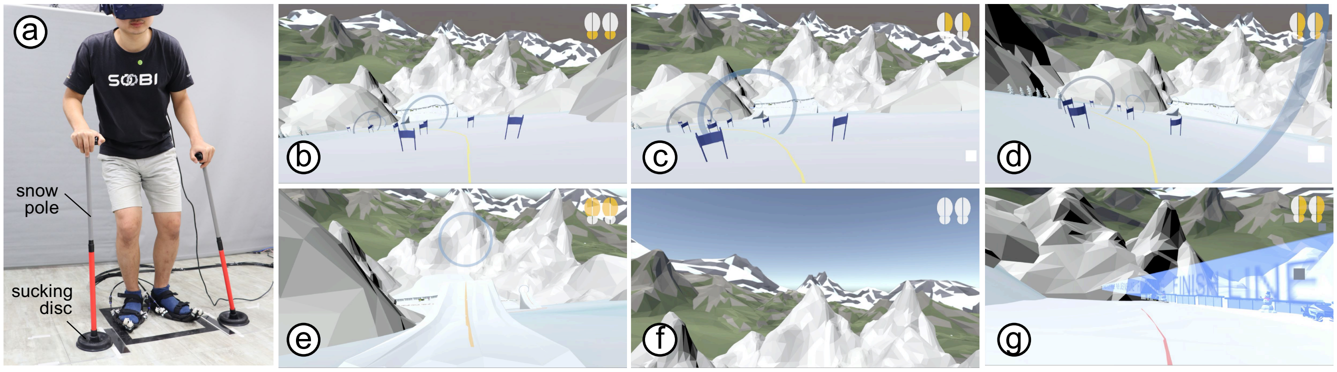

Figure 7: The installation and views of the Ski experience. (a) The snow pole stick on the ground beside the user assist for him shadowing the experience and his balance. Kinesthetic force feedbacks were invoked at feet for (b) speeding, (c)(d) taking a (left) turn, (e) riding on a ramp, (f) air time and landing (not on display), and (g) a left parallel stop.

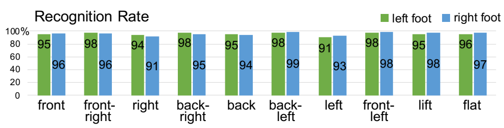

Figure 8: Recognition Rate of Shape Patterns for Each Foot.

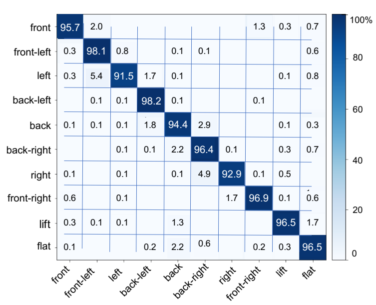

Figure 9: Normalized confusion matrix of shape patterns across feet.

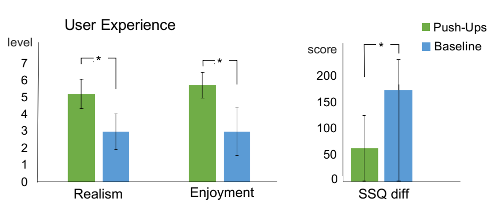

Figure 10: User ratings on realism and enjoyment, and scores on difference SSQ. The error bars indicate standard deviations.

feet, it felt like I was skiing down the slope." The sense of control was specifically mentioned by two of the participants and played an important role in improving the rating of enjoyment as they described.

We also asked for some suggestions regarding the skiing experience. Ten participants mentioned that implementing a sense of speed, preferably cold wind, would improve the experience. We also received advice about moving the ski poles simultaneously when Push-Ups was actuated, spraying a small spill of water or snowflakes on the face, and even changing the floor the users were standing on. As one remarked, "It would be better if the floor creates a soft and wet feeling when stepping on it." In addition, two participants hoped the feedback could provide multiple levels of feedback.

7 LIMITATION

While we have demonstrated effective motion output on feet with *Push-Ups*, this work is subject to a set of limitations.

Our implementation only supports the same elevation height at full inflation. Notably, a pneumatic muscle has the potential to create different heights of elevation within the range of radial expansion for Push-Ups. For instance, pairing each muscle with a proximity sensor can create a close-loop control that automatically adjusts inflation to reach a target height against the user's weight. However, the expansion level has a direct interaction with the muscle body's softness, which would affect the haptic texture of footsteps. In another direction, one could exploit this property for simulating materiality. Moreover, future works can explore time-varying inflation to simulate the sensation of changing texture underneath the feet.

Like other pneumatic-based share-forming interfaces, air-compressors are necessary as the source of driving force for *Push-Ups*. In our case needing a scale of force for lifting the weight of an adult, a powerful air compressor is indispensable and noises coming along with driving it up is unavoidable. As a workaround for reducing noise, one can distance the air-compressor from the end effectors on the user, such as placing it outside of the building.

In addition, the end effectors on the user's feet can impose limits on the user's free walking or, worse, get the user tripped by the pipes in free walking. Future studies can exploit redirected walking to expand the virtual walking range [21] while preventing users from getting stumbled. The reaction time to full inflation took a little more than one second in our implementation, which may not be sufficient for real-time applications. Adopting more powerful air compressors and driving the feedback in advance with prediction can reduce the perceived reaction time.

It is worth noting that shape-changing interface on shoes that can tilt or elevate the user from foot need to pay dedicated care on safety. The push force from feet bottom unwitting to or unexpected by the user can cause him or her to lose balance. Even the user has been prepared for the motion output on feet, instantaneous or continuous changes can lead to imbalance. In our ski experience, the user is offered with ski poles to keep the balance. In the earthquake experience, we let the user stand by a desk as balance support. In the similar vein, we chose to limit the applications for a standing type of activity for safety concerns, as walking or running would produce much higher impacts to the shoes and thus the air muscles. For patterns with single muscle supporting the formation such as the back-left pattern, the supporting muscle would be placed at a higher risk of breakdown. This requires future engineering study into fabrication of pneumatic muscles for supporting more intensive interaction.

Regarding generality, *Push-Ups* is not limited to experiencing ski. Our immediate future work looks into simulating earthquake taking place in a virtual environment for earthquake education or emergency training. For instance, controlling frequency and behaviors of the motion outputs on the user's feet allows to simulate the progression of p-wave and s-wave stages in an earthquake. In addition, *Push-Ups* has potentials to simulate stepping types of motions such as reacting to foot interacting with virtual widgets on floor and taking virtual stairs [20]. emphPush-Ups can be be used in seated experience, such as to simulate the haptic feel of the foot pedal [14] and road condition in a simulated drive.

Finally, we conducted our study with a similar age group. Previous research has shown that human capability in the proprioception of the ankle differs across culture and deteriorates with age [29]. Future researchers must learn the impact of different age groups on the perception of feedback on feet.

8 CONCLUSION

We have presented *Push-Ups* as a method to generate motion output on the users' feet for enhancing their foot-based kinesthetic experience in VR. We detailed the implementation and demonstrate its capabilities with a VR ski experience. This work only explored a limited set of functions of haptic output for shape-forming shoe bases. Future works can extend the feedback for multilevel elevation, simulating materiality and dynamic ground texture.

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