# PAVES: Pneumatic And Vibrotactile Enhanced Shoes for terrain simulation in virtual environments on a treadmill

Marco Gabrecht
Technical University of Applied Sciences Lübeck
Lübeck, Germany
Fraunhofer IMTE
Lübeck, Germany
marco.gabrecht@th-luebeck.de

Chenwei Huang
East China University of Science and Technology
Shanghai, China
Technical University of Applied Sciences Lübeck
Lübeck, Germany
Chenwei.Huang@studt.th-luebeck.de

Denys J.C. Matthies
Technical University of Applied Sciences Lübeck
Lübeck, Germany
Fraunhofer IMTE
Lübeck, Germany
denys.matthies@th-luebeck.de

Hans-Christian Jetter
University of Lübeck
Lübeck, Germany
jetter@imis.uni-luebeck.de

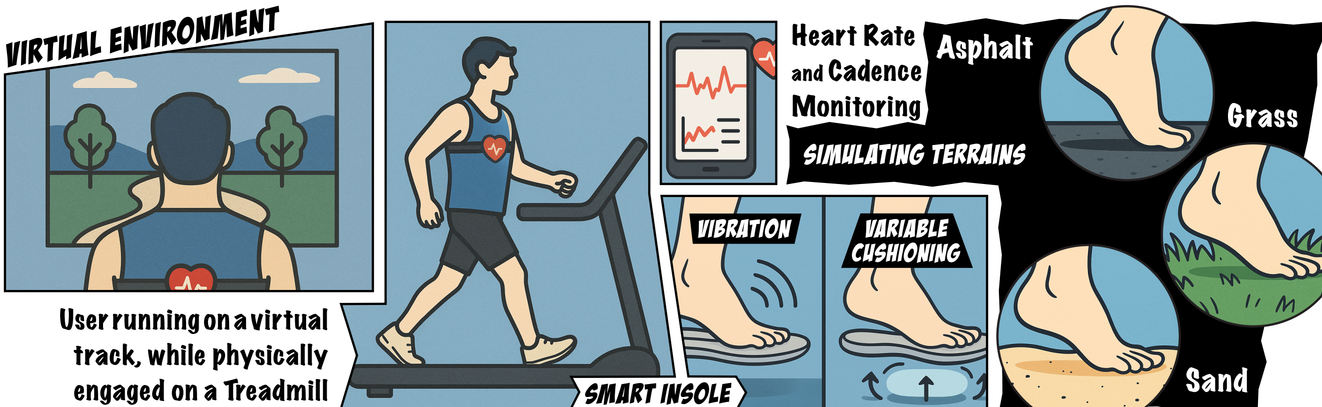


**Figure 1: Participants run on a treadmill equipped with smart insoles that simulate different terrains: asphalt, grass, and sand, through vibration and pneumatic feedback. Real-time heart rate and cadence data are analyzed to understand energy expenditure under varying terrain simulation.**

## Abstract

Simulating terrains to enhance immersion in virtual environments can improve user experience and may also benefit rehabilitation. In this paper, we present a method to physically simulate terrain with a hybrid-actuation insole prototype based on pneumatic and vibrotactile feedback. We utilize six coin cells vibration motors and 3D-printed pneumatic valve system that can inflate and deflate air pressure chambers in the midsole. We ran an exploratory lab study on a treadmill to understand how simulated terrains, including asphalt, grass, and sand is perceived by the user. Our study demonstrates that participants perceived the simulated terrains as distinct and convincing, with the sand terrain, in particular, being rated as the most realistic among the conditions tested.



*PETRA '25, Corfu Island, Greece*

ACM ISBN 979-8-4007-1402-3/25/06
https://doi.org/10.1145/3733155.3733202

## CCS Concepts

• **Human-centered computing** → **Haptic devices**.

## Keywords

Virtual Reality (VR) Haptic Feedback, Vibrotactile Stimulation, Pneumatic Actuation, Terrain Simulation, Wearable Technology, Haptic Footwear, 3D Printing, User Study, Immersive Environments

**ACM Reference Format:**

Marco Gabrecht, Chenwei Huang, Denys J.C. Matthies, and Hans-Christian Jetter. 2025. PAVES: Pneumatic And Vibrotactile Enhanced Shoes for terrain simulation in virtual environments on a treadmill. In *The PErvasive Technologies Related to Assistive Environments (PETRA '25), June 25–27, 2025, Corfu Island, Greece.* ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3733155.3733202

## 1 Introduction

Using feet in HCI is not a new trend. With Extended Reality, research shows novel interaction concepts that extend to feet and toes [24]. In Virtual Reality (VR), ongoing research mainly aims to enhance immersion by better integrating physical and virtual

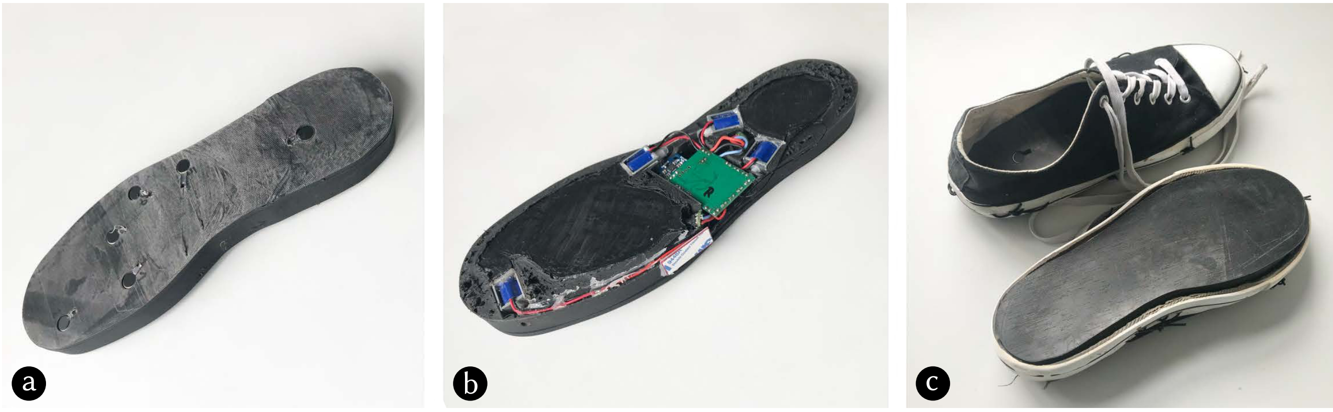


**Figure 2: We further developed the prototype PNEUSHOE [12]. (a) Top view of the insole showing the mounted coin-cell vibration motors. (b) Bottom view of the insole, illustrating the pneumatic valves (in blue) and the printed circuit board (in green) housing all electronics and the integrated battery. (c) The insole placed within a modified shoe, replacing the original sole to form the complete footwear prototype.**

elements [35]. While current VR systems offer advanced visual and auditory feedback, tactile interaction at the feet still remains relatively underexplored. This underutilization is notable given that the foot has a higher density of sensory cells than the human face [18], providing a sensitive platform for haptic interaction. Despite this potential, foot-based wearable interfaces are not yet common [1], with commercial products largely constrained to specialized applications such as running performance analysis or gaming [14, 22, 38, 39].

To enhance the sense of presence in virtual environments, one central challenge to simulate terrains the user is running on. Previous investigations have focused on delivering frictional feedback, vibrotactile cues [17, 36, 40], or replicating specific conditions like icy or muddy surfaces [7, 23]. However, many existing approaches rely on tethered, cumbersome equipment that can restrict movement and reduce the overall level of immersion.

This work takes an initial step toward addressing these limitations by introducing a VR shoe prototype that integrates vibrotactile and pneumatic feedback when running on a treadmill. Multiple terrains are simulated, ranging from hard to soft surfaces. An exploratory user study assesses the perceived realism of these simulations, providing preliminary insights that may guide future development of more integrated, human-centric cyber-physical human systems (CPHS) for foot-based haptic feedback. In accordance to Wobbrock and Kientz [50], this research embodies an empirical contribution.

## 2 Related Work

For several decades, research in human-computer interaction (HCI) and cyber-physical & human systems (CPHS) investigates foot interfaces as a means of providing haptic feedback and capturing user input. Still, this remains an active area of research, with ongoing exploration of novel foot augmentation interfaces [31].

### 2.1 Sensing

Academic efforts have explored various sensing modalities to capture locomotion characteristics and environmental interactions. For instance, inertial measurement units (IMUs) have been used to analyze gait and movement [15, 19], while in particular force sensing resistor (FSR) pressure sensors help monitor ground contact and force distribution [9, 10]. Also Capacitive Sensing (CapSense) was utilized to detect walking styles [13] and floor types [20]. Other sensor technologies, such as temperature and humidity monitoring [25, 30] or strain gauges [5] have broadened the range of measurable foot-related parameters. Regarding plantar pressure, the most common sensor type is resistive, following Castro et al. [3]. The current state-of-the-art in multimodal sensing today typically relies on neural networks [4, 33, 48, 52].

### 2.2 Actuation

In contrast, fewer studies focus on actuators that provide haptic feedback. Vibrotactile displays, employing vibration motors, represent a common approach and have been used to deliver various cues, including directional guidance, textures, and alerts [8, 11, 19, 21, 29, 34, 44, 49, 51]. Beyond vibrotactile solutions, researchers have explored actuators such as shape-memory alloys, air chambers, and friction-modulation mechanisms to recreate sensations associated with uneven or dynamically changing terrains [28, 45–47, 54]. For example, Strohmeier et al. [35] demonstrated that foot-based actuators can simulate material properties like compliance and elasticity, enhancing immersion in VR and AR. Similarly, "Gilded Gait" [37] employed vibrotactile feedback in insoles to convey various ground textures, suggesting that subtle haptic cues at the feet can alter how users perceive and interact with their environment.

### 2.3 Terrain Simulation

So far, friction-based terrain simulations have garnered attention [6]. Kato et al. [17] replicated forward motion using frictional feedback, outperforming vibratory cues, while others examined icy or muddy conditions [7], variable-friction devices [23], and friction-shifting prototypes like bARefoot [36] and FrictShoes [40]. Beyond friction, audio-haptic integration [27, 41], insights into tactile-foot perception [43], electrotactile stimulation [42], shape-changing floors [16], and foot-based tactons [2] have further enriched the realism of virtual walking experiences.

# 3 Prototype

While advancements in research highlight the promise of foot-based haptics, many existing systems rely on external power sources or are bulky and tethered. Such constraints can limit natural movement and detract from the intended immersive experience. By focusing on untethered, battery-powered solutions that integrate multiple feedback modalities, current research aims to overcome these hurdles and foster more naturalistic interactions [41]. Ultimately, these efforts align with the broader vision of Cyber-Physical Human Systems (CPHS) [26, 53], which place humans at the center.

Recently, we advanced a previous prototype that is wireless, not cumbersome and offering real-time sensing and actuation [12]. Our latest iteration can be seen in Figure 2. The insole features two air pressure chambers that are 11mm thick, including 10mm thick valves, which are strong enough to maintain pressure while walking. To save space and weight, a compressor was omitted, and the user is utilized to generate pressure. The chambers have different sizes, allowing pressure to be stored upon strong impacts and then distributed as needed. The air pressure sensors are designed to withstand the impact of a 100kg person jumping, yet they can also measure finer pressure changes. The top layer, facing the user's sole features a layer with six coin-cell vibration motors. To drive the valves and vibration motors, the system employs a MOSFET power stage. Specifically, the SSM3K7002KFU, LF MOSFET is chosen for its capacity to handle continuous currents of up to 400 mA and peak pulses as high as 1.2 A.

The additional electronics are housed on a dedicated PCB to save space and are the same size as the battery. The battery is expected to last approximately 6 hours. An ESP32 microcontroller was used, which can be controlled via Wi-Fi and streams the measurement data, recorded at 100Hz, to the cloud database InfluxDB. The measurements of pressure, both in the chambers and the movement from the accelerometer and gyroscope, as well as the internal state, can be analyzed later and are also streamed to a web interface on the device itself if needed.

# 4 Evaluation

We pose the following research question *"$RQ_{Main}$: How can we simulate different terrains in a virtual environment?"*

Since simulating terrain with changing cushioning in combination with vibration is yet to be researched, we designed an exploratory study to construct validity and to create empirical validity. We designed four hypotheses to address our research question.

## 4.1 Hypotheses

- **H1:** The participants can be tricked to think they are on a different surface.
- **H2:** The simulation of varied surfaces is effective due to the foot's reduced sensitivity and the visual stimulus from the video enhances the perceived illusion.
- **H3:** The different surfaces have an significant impact on heart rate.
- **H4:** The different surfaces have an significant impact on cadence.

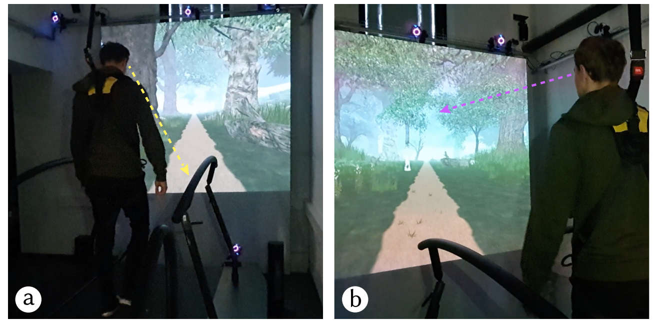


**Figure 3: a) The participant is looking down to his feet while running - the yellow arrow points to the direction of their gaze. b) The participant looking straight ahead while running - the purple arrow points in the direction of his gaze.**

## 4.2 Apparatus

The equipment needed in the study includes a treadmill, a projection screen with a projector, a heart rate monitor (chest strap, model COOSPO H808S), RBG & IR cameras as well as our insole prototype, as depicted in Figure 2. The study setup is depicted in Figure 3.

## 4.3 Procedure and Task

First, each participant will run on the treadmill for 2 minutes with the actuator which is deactivated. The virtual running video is not played during this period.

Next, in front of the projection screen that plays virtual running videos, participants equipped with the actuator insoles run on the treadmill for 2 minutes in each of the following simulated terrains and answer online questions about the simulated terrains they have just experienced directly after.

Through the web interface, which controlles our insole prototype, we can set certain values, such as the target pressure, or direct control of valves and vibration in response to specific events such as pressure spikes or changes. We created 3 terrain simulations ("profiles"):

- For **asphalt**, the pressure is set to a high value of 3800, with vibrations at nearly full power (PWM of 244) for 50 ms upon ground impact.
- For **grass**, the pressure is set to a moderate value of 3000 and then equalized by the rest of the time. This creates a shift between the front and back chambers, allowing the participant to sink into the shoe where more force is applied. The vibration is set to a PWM of 55 whenever the pressure in the front or back increases by more than 60 above a smoothed baseline value: `baselineH = baselineH * 0.990 + sensorValueH * 0.010`.
- For **sand**, the pressure is slightly lower at 2800, while the vibration is stronger, with a PWM value of 70.

These values were determined in an empirical manner by the authors.

Finally, each participant needs to fulfill an online questionnaire about their experience (see Appendix), perceived similarity to real environments, and the effect of using the insoles.

## 4.4 Participants

We recruited 8 participants, which were males, aged between 21 and 22, college students. They are all healthy and have various running experiences.

## 4.5 Data Gathering

During each run, use the camera to continuously record running motion of the participants from their sideways. A heart rate monitor worn by participants collects real-time heart rate data, which is sent to a smartphone app for automatic analysis and chart generation. Recording real-time heart rate allows us to compare average heart rate changes across different simulated terrains. According to the literature, elevated heart rates correlate with higher calorie burn and energy expenditure, which can vary by terrain. For instance, running on sand, barefoot or with shoes, requires more energy than running on grass. By comparing each participant's heart rate across terrains, we can estimate relative energy expenditure and evaluate how closely the simulated terrains match real-world conditions.

## 4.6 Qualitative data collection

After completing all experimental conditions, we provide each participant with an online questionnaire to gather qualitative data on their experience, perceived similarity to real environments, and the effect of using the insoles. The questionnaire can be seen in the Appendix.

# 5 Results

## 5.1 Questionnaire Data

As seen in the appendix, the questionnaire consists of two parts. The first part includes nine questions, answered during three 3-minute breaks, each following a treadmill session on one of the simulated terrains. In this section, we will show the most interesting analyses.

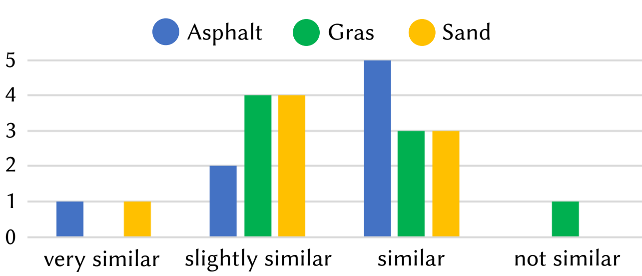


**Figure 4: The diagram shows the distribution of answer to the question *"How similar is the asphalt (grass/sand) simulated by the insole to the one in real life?"*.**

*5.1.1 Subjective similarity of terrains.* As seen in Figure 4, the results vary slightly:

- For *asphalt*, 1 participant found the simulated asphalt terrain very similar, 2 participants found it similar, 5 participants found it slightly similar, and no participants found it not similar.
- For *grass*, none of the participants found the simulated grass terrain very similar, 4 participants found it similar, 3 participants found it slightly similar, and 1 participant found it not similar.
- For *sand*, 1 participant found the simulated sand terrain very similar, 4 participants found it similar, 3 participants found it slightly similar, and none of the participants found it not similar.

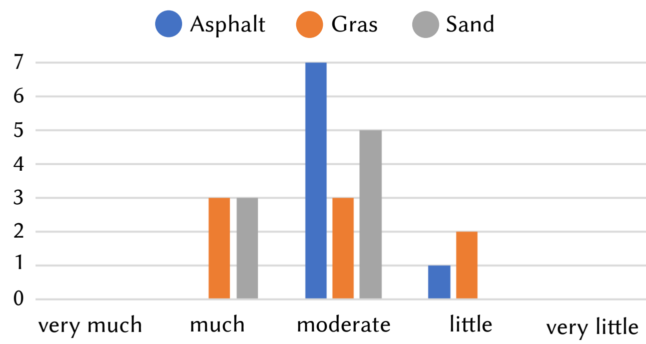


**Figure 5: This diagram shows the distribution of answer to the question *"How much do you strain your lower muscles and ankle joints when running on simulated asphalt/grass/sand?"*.**

*5.1.2 Subjective strain of terrains.* Looking at Figure 5, the results can be interpreted as follows:

- For *asphalt*, none of the participants felt they strained their lower muscles and ankle joints "very much" or "much" when running on the simulated asphalt. However, 7 participants reported a moderate strain, and a single participant reported a little strain of their lower muscles and ankle joints.
- For *grass*, none of the participants felt they used their lower muscles and ankle joints "very much" when running on the simulated grass. Three participants reported "much" strain, 3 participants reported a moderate strain, and 2 participants reported a little strain of their lower muscles and ankle joints.
- For *sand*, none of the participants felt they strained their lower muscles and ankle joints "very much" when running on the simulated sand. Three participants reported much strain, 5 participants reported a moderate strain, and none of the participants reported a little or very little strain of their lower muscles and ankle joints.

In the second part of the questionnaire, the test subjects were asked to rank the strain of different terrains ( "Please rank the strain of lower leg muscles and ankle joints in the three simulated terrains from largest to smallest.")

$$M_{OverallRating} = \frac{\sum_{i=1}^{n}(Frequency \times Weight)}{SampleSize}$$

For comparison, a Friedman rank test was conducted $\chi^2(2) = 1.0$ where $\alpha = 0.05$: 5.99 and showing the rejection of significance. There is no statistically significant difference in the perceived strain on lower leg muscles and ankle joints across the three simulated terrains: asphalt ($M$=2.13), sand ($M$=2.13), and grass ($M$=1.75).

*5.1.3 Realism of terrains.* The distribution of answered is shown in Table 1.

**Table 1: The table shows the answers to the questions "Which of the terrains simulated by this insole do you think is the most (or least) similar to the real one?"**

| | Asphalt | Grass | Sand |
|---|---|---|---|
| Most realistic | 1 | 1 | 6 |
| Least realistic | 0 | 6 | 2 |

The results can be explained as follows:

- For the *most realistic* terrain, 1 participant selected asphalt, 1 participant selected grass and 6 participants selected sand.
- For the *least realistic* similar terrain, no one selected asphalt, 6 participants selected grass and 2 participants selected sand.

It's clear even without statistical testing that Sand is overwhelmingly rated as most realistic, while Grass is most often rated as least realistic. A Chi-Square test of independence revealed a significant difference in perceived realism across terrains, $\chi^2(2, N = 16) = 6.58$, $p < .05$.

*5.1.4 Improvement of Running Experience.* In our 10th and 11th question, aims to understand to what extent the system has improved treadmill running experience. Only 3 of 8 participants agree that our 4D running system improves their experience compared to their usual treadmill workout experience, while rest of them disagree.

Our qualitative data underpinned our obvious finding from the video recordings of the users. We found that almost all participants looked down to their feet at some point while running. To quantify that:

- 1 person has never looked underfoot while 1 person looks at their feet almost the whole time.
- 1 person is in a state of looking at the screen or looking at his feet and switching at any time, and the switching interval is irregular.
- 1 person looks at his feet every 5 seconds on average and the remaining 4 participants looked at their feet for an average of 10-15 seconds.

A binomial test showed no significant difference from chance in perceived experience improvement, $p = .73$, with only 3 out of 8 users reporting a better experience.

## 5.2 Sensor Data

*5.2.1 Overall performance differences by heart rate and cadence.* The first statistical analysis examines the effect differences on the terrains based on varying heart rate and cadence (see Table 2). The results of the ANOVA are presented in Tables 3 and 4.

As indicated in Table 3, there was no statistically significant difference in heart rate across the different terrains, as evidenced by the high $p$-value ($p$ = 0.46). Similarly, the ANOVA results for cadence, shown in Table 4, also indicated no significant differences between terrains ($p$ = 0.7). These findings suggest that terrain type does not significantly influence heart rate or cadence under the conditions tested.

**Table 2: This table shows the average real-time heart rate (unit: bpm) measured by the heart rate belt for 8 participants while running on three simulated terrains, including a control condition. Further it shows the cadence (Unit: steps/minute).**

| | **Asphalt** bpm / steps | **Grass** bpm / steps | **Sand** bpm / steps | **Control Cond.** bpm / steps |
|---|---|---|---|---|
| **P1** | 115 / 161 | 108 / 152 | 121 / 155 | 106 / 153 |
| **P2** | 112 / 146 | 106 / 144 | 109 / 140 | 110 / 142 |
| **P3** | 116 / 161 | 120 / 156 | 122 / 154 | 121 / 158 |
| **P4** | 126 / 159 | 128 / 154 | 128 / 152 | 126 / 154 |
| **P5** | 127 / 138 | 126 / 132 | 129 / 135 | 125 / 133 |
| **P6** | 142 / 160 | 143 / 155 | 146 / 157 | 128 / 158 |
| **P7** | 129 / 163 | 125 / 150 | 130 / 145 | 127 / 152 |
| **P8** | 137 / 184 | 130 / 177 | 144 / 185 | 117 / 169 |

*5.2.2 Pairwise differences by heart rate.* In the second analysis, we aimed to determine whether there were statistically significant differences between pairs of terrains, and whether these differences could be attributed to real effects rather than random variation. To evaluate this, we conducted paired $t$-tests.

The results of the $t$-tests are presented below, including the corresponding $p$-values.

We can see from the table that the $p$-values obtained for all sand-related groups are all lower than 0.05, which means that there is a significant difference between running on sand and running on other terrains. Combining the specific values in Table 2, we found that, except for one participant, the rest of the participants running on the simulated sand had higher heart rates than the other two simulated terrains as well as the control group, so it can be concluded that the average heart rate of running on the simulated sand was higher than that in the other two simulated terrains as well as the control group.

Based on literature, such as by Sassi et al. [32], we know that the energy cost of running on sand is significantly higher than that of running on grass. What's more, running on natural 'off-road' terrain demands higher energy costs than running on the road (like

**Table 3: Results of the ANOVA repeated measures for heart rate.**

| Source of Variation | Sum of Squares | df | F-value | $p$-value |
|---|---|---|---|---|
| Between Terrains | 317.84375 | 3 | 0.893705 | 0.456596 |
| Residual | 3319.37500 | 28 | | |

**Table 4: Results of the ANOVA repeated measures for cadence.**

| Source of Variation | Sum of Squares | df | F-value | $p$-value |
|---|---|---|---|---|
| Between Terrains | 248.125 | 3 | 0.481587 | 0.697723 |
| Residual | 4808.750 | 28 | | |

asphalt). In addition, average heart rate over time correlates with energy expenditure, the higher the heart rate, the higher the energy expenditure. Summing up these research findings, we can conclude that the average heart rate running on sand is greater than that of other terrains (including grass and asphalt). In summary, our results coincident with the findings of the literature review.

*5.2.3 Correlation to the questionnaire results.* Comparing our sensor data to the questionnaire data also reveals some findings. For instance, the distribution of answers to the 8th and 9th questions in the questionnaire supports the above results and possible explanations for the unexpected results. From Table 1, we can see that sand and grass received the highest number of votes with 6 votes each, making them the most and least similar terrain that participants considered, respectively. Although a very small number of individual votes are distributed in other positions, reflecting individual differences, 75% of the votes undoubtedly reflect credibility.

However, the results reveal a more nuanced picture. In the first part of the questionnaire (see Table 4), participants evaluated the similarity of each simulated terrain during short rest periods immediately following their exposure to that specific terrain. In contrast, the second part of the questionnaire was completed after all experimental procedures had concluded, requiring participants to make retrospective judgments.

Interestingly, when comparing the two sets of responses, we observe a shift in perception: asphalt, which was not initially rated as the least similar terrain, is later perceived as the least realistic, replacing grass in that position. This change highlights the potential influence of temporal context and memory on subjective evaluations.

Another method to look at the data, particularly the realism ratings, is to transform the results into a quantitative 4-point ordinal scale (see Table 5).

**Table 5: We divided the degree into four equal quartiles from 0 to 100%, and assigned them to four options in turn. We set "not similar" to 0, and then go up in turn, respectively n/3, 2n/3, n, (n>0). The values shown are obtained according to the weighting method. The higher score, the more similar.**

| | Asphalt | Sand | Grass |
|---|---|---|---|
| Score | 10n/3 | 14n/3 | 11n/3 |

In result, sand received scores the highest similarity score, suggesting participants found it to be the most realistic simulation overall. Grass comes next, and Asphalt scored lowest, meaning it was perceived as the least similar.

In addition to perceived realism, we assessed another metric: the degree of calf muscle and ankle joint engagement. Similar to the previous question, this was asked in both the first and second parts of the questionnaire. As shown in Table 5, during the first part, 7 out of 8 participants rated asphalt as “moderate,” while sand elicited the highest levels of muscular engagement, followed by grass.

However, the distribution of responses shifted in the second part. In Question 7, sand and asphalt received the highest combined scores, while grass was rated lowest. This suggests that, upon reflection, participants perceived both sand and asphalt as requiring more muscular effort, while grass was perceived as less demanding.

**Table 6: This table presents the $p$-values obtained by longitudinally comparing each two sets of data in Table 2 about bpm. We take the first three digits after the decimal point and round up. (A represents asphalt, G represents grass, S represents sand and CC represents control condition.)**

| | A vs. G | A vs. S | G vs. S | A vs. CC | G vs. CC | S vs. CC |
|---|---|---|---|---|---|---|
| $p$ | 0.185 | 0.032 | 0.022 | 0.100 | 0.228 | 0.046 |

## 6 Discussion

In this study, we aimed to simulate different terrains on a treadmill with a smart insole prototype, thus enhancing the realism and possibly running experience in VR environments. The results from our exploratory study presents a mixed but insightful picture regarding the efficacy of our prototype and method. Below, we discuss the findings in relation to our initial hypotheses, the limitations of our study, and potential future directions.

### 6.1 Summary of Findings

*6.1.1 Perceived Similarity of Simulated Terrains.* The questionnaire responses indicate that participants generally perceived the simulated terrains as somewhat realistic, with sand being the most convincingly simulated terrain. This is consistent with our hypothesis **H1**, suggesting that participants can be tricked into believing they are running on different surfaces. However, the variability in responses also highlights areas where the simulation could be improved. For instance, the simulated grass terrain was less convincing, as indicated by several participants who found it only slightly similar or not similar to real grass.

*6.1.2 Muscle and Joint Engagement.* Participants reported varying levels of muscle and joint engagement across different terrains. The simulated sand terrain required the most muscle and joint engagement, which aligns with real-world expectations. This finding partially supports our hypothesis **H2**, which posited that visual stimuli combined with foot feedback would enhance the perceived realism. However, the asphalt simulation, expected to be similar to a treadmill surface, did not significantly alter the engagement levels, suggesting that the prototype may need further refinement for smoother surfaces.

*6.1.3 Heart Rate and Cadence Analysis.* Our analyses revealed no significant differences in heart rate or cadence across the simulated terrains, except for sand, which consistently showed higher heart rates. This aligns with literature indicating that running on sand requires more energy and thus results in a higher heart rate. However, the lack of significant differences for other terrains suggests that either the current prototype might not provide sufficiently distinct feedback to differentiate between other terrains, or other terrains may not evoke higher physical effort.

## 6.2 Answering Hypotheses

**H1:** Our study *supports* this hypothesis, as participants were often convinced they were on different terrains, particularly with the sand simulation.

**H2:** The hypothesis is *partially supported*. Participants who looked at their feet rated the realism lower than those who looked less at their feet.

**H3:** This hypothesis may be *partly supported*, as there were was a significant differences in heart rate when running on simulated sand.

**H4:** This hypothesis is *rejected*, as the cadence did not show significant variation between different simulated terrains.

## 6.3 Limitations and Future Work

*6.3.1 External Validity.* In this paper, we evidenced initial validity with a limited sample size of eight young male college students. In this scope, we gathered valuable insights to guide further development. Future studies involving a larger and more diverse sample size and different contexts will be essential to validate robustness and ecological validity of our findings and thus enhancing their generalizability.

*6.3.2 Limited Hardware.* The study also identified opportunities to improve the prototype, particularly in enhancing the feedback mechanism to increase realism and distinctiveness of terrains such as grass and asphalt. This may involve refining the hardware or changing the type of feedback mechanisms, such as incorporating different actuators to deliver higher-fidelity haptic cues.

*6.3.3 Qualitative assessment and the nature of a lab study.* Questionnaire-based feedback has advantages and limitations. In our case, it proved reliable for evaluating perceived realism. However, early in the experiment, some participants orally reported difficulty perceiving the simulated asphalt terrain, likely due to its similarity with the treadmill surface and the absence of a comparative reference. By the end of the session, after experiencing all terrain types, participants were better able to make informed assessments. These findings highlight the importance of timing and context in subjective evaluations and point toward methodological refinements for future usability studies, including moving from a lab study to a field study.

# 7 Conclusion

In this paper we utilized a smart insole prototype with a hybrid-feedback insole prototype based on pneumatic and vibrotactile feedback. We conducted an empirical evaluation to understand a new methodology to enrich the locomotion experience VR environments by simulating various terrains. The initial outcomes, especially in replicating sandy surfaces, are encouraging, and addressing the identified limitations will enable meaningful refinements. Strengthening the prototype and implementing these improvements will help create a more immersive and authentic VR experience, ultimately broadening the scope of this technology's applications.

# References

[1] Neil Aitken. 2019. Most Used Features of Smartwatches. https://whatphone.com.au/guide/most-used-features-of-smartwatches Section: Apple.

[2] Jan Anlauff, Joyce Fung, and Jeremy R. Cooperstock. 2017. VibeWalk: Foot-based tactons during walking and quiet stance. In *2017 IEEE World Haptics Conference (WHC)*. 647–652. doi:10.1109/WHC.2017.7989977

[3] Pedro Castro-Martins, Arcelina Marques, Luís Coelho, Mário Vaz, and João Santos Baptista. 2024. In-shoe plantar pressure measurement technologies for the diabetic foot: A systematic review. *Heliyon* 10, 9 (2024).

[4] Hsiao-Lung Chan, Rou-Shayn Chen, Cheng-Chung Kuo, Yi-Tao Chen, Jiunn-Woei Liaw, Guo-Sheng Liao, Wan-Ting Lin, Shih-Hsun Chien, and Ya-Ju Chang. 2024. Laser-light cueing shoes with integrated foot pressure and inertial sensing for investigating the impact of visual cueing on gait characteristics in Parkinson's disease individuals. *Frontiers in Bioengineering and Biotechnology* 12 (2024), 1334403.

[5] Harish Chander, Reuben F Burch, Purva Talegaonkar, David Saucier, Tony Luczak, John E Ball, Alana Turner, Sachini NK Kodithuwakku Arachchige, Will Carroll, Brian K Smith, et al. 2020. Wearable stretch sensors for human movement monitoring and fall detection in ergonomics. *International journal of environmental research and public health* 17, 10 (2020), 3554.

[6] Donald Degraen, Martin Feick, Serdar Durdyyev, and Antonio Krüger. 2024. Prototyping Surface Slipperiness using Sole-Attached Textures during Haptic Walking in Virtual Reality. In *Proceedings of the International Conference on Mobile and Ubiquitous Multimedia*. 95–105.

[7] Judith E Deutsch, Rares F Boian, Jeffrey A Lewis, Grigore C Burdea, and Andrea Minsky. 2008. Haptic effects modulate kinetics of gait but not experience of realism in a virtual reality walking simulator. In *2008 Virtual Rehabilitation*. IEEE, 36–40.

[8] Abdulmotaleb El Saddik, Mauricio Orozco, Mohamad Eid, and Jongeun Cha. 2011. *Haptics technologies: Bringing touch to multimedia*. Springer.

[9] Don Samitha Elvitigala, Denys JC Matthies, Löic David, Chamod Weerasinghe, and Suranga Nanayakkara. 2019. GymSoles: Improving Squats and Dead-Lifts by Visualizing the User's Center of Pressure. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–12.

[10] Don Samitha Elvitigala, Denys JC Matthies, and Suranga Nanayakkara. 2020. StressFoot: Uncovering the potential of the foot for acute stress sensing in sitting posture. *Sensors* 20, 10 (2020), 2882.

[11] Don Samitha Elvitigala, Denys JC Matthies, Chamod Weerasinghe, and Suranga Nanayakkara. 2021. GymSoles++: Combining Google Glass with Smart Insoles to Improve Body Posture when Performing Squats. In *The 14th PErvasive Technologies Related to Assistive Environments Conference*. 48–54.

[12] Marco Torge Gabrecht, Hengyu Wang, and Denys Jörg Christian Matthies. 2023. PneuShoe: A Pneumatic Smart Shoe for Activity Recognition, Terrain Identification, and Weight Estimation. In *Proceedings of the 8th international Workshop on Sensor-Based Activity Recognition and Artificial Intelligence*. 1–5.

[13] Marian Haescher, Denys JC Matthies, Gerald Bieber, and Bodo Urban. 2015. Capwalk: A capacitive recognition of walking-based activities as a wearable assistive technology. In *Proceedings of the 8th ACM International Conference on PErvasive Technologies Related to Assistive Environments*. 1–8.

[14] YUKO ICHIKAWA. 2021. Cybershoes for Quest & SteamVRVR Gaming Shoe. https://www.cybershoes.com/us/features/

[15] Frank Imbach, Robin Candau, Romain Chailan, and Stephane Perrey. 2020. Validity of the Stryd power meter in measuring running parameters at submaximal speeds. *Sports* 8, 7 (2020), 103.

[16] Seungwoo Je, Hyunseung Lim, Kongpyung Moon, Shan-Yuan Teng, Jas Brooks, Pedro Lopes, and Andrea Bianchi. 2021. Elevate: A Walkable Pin-Array for Large Shape-Changing Terrains. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 127, 11 pages. doi:10.1145/3411764.3445454

[17] Ginga Kato, Yoshihiro Kuroda, Kiyoshi Kiyokawa, and Haruo Takemura. 2018. Force rendering and its evaluation of a friction-based walking sensation display for a seated user. *IEEE Transactions on visualization and computer graphics* 24, 4 (2018), 1506–1514.

[18] Michael Locke. 1984. Epidermal cells. In *Biology of the Integument: Invertebrates*. Springer, 502–522.

[19] Denys J.C. Matthies, Don Samitha Elvitigala, Annis Fu, Deborah Yin, and Suranga Nanayakkara. 2021. MobiLLD: Exploring the Detection of Leg Length Discrepancy and Altering Gait with Mobile Smart Insoles. In *The 14th PErvasive Technologies Related to Assistive Environments Conference (PETRA 2021)*. Association for Computing Machinery, New York, NY, USA, 37–47. doi:10.1145/3453892.3453896

[20] Denys JC Matthies, Franz Müller, Christoph Anthes, and Dieter Kranzlmüller. 2013. ShoeSoleSense: proof of concept for a wearable foot interface for virtual and real environments. In *Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology*. 93–96.

[21] Anita Meier, Denys JC Matthies, Bodo Urban, and Reto Wettach. 2015. Exploring vibrotactile feedback on the body and foot for the purpose of pedestrian navigation. In *Proceedings of the 2nd international Workshop on Sensor-based Activity Recognition and Interaction*. 1–11.

[22] Dennis Metz. 2022. Digitsole Smartshoe ist ein selbstschnürender Sneaker. https://www.gadget-rausch.de/digitsole-smartshoe-ist-ein-

selbstschnuerender-sneaker/

[23] Guillaume Millet, Martin Otis, Daniel Horodniczy, and Jeremy R Cooperstock. 2017. Design of variable-friction devices for shoe-floor contact. *Mechatronics* 46 (2017), 115–125.

[24] Florian Müller, Daniel Schmitt, Andrii Matviienko, Dominik Schön, Sebastian Günther, Thomas Kosch, and Martin Schmitz. 2023. Tictactoes: Assessing toe movements as an input modality. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–17.

[25] A Mohamed Nazeer, S Sasikala, M Sathish Kumar, M Yogeshwaran, K Veeramani, and R Vigneshwaran. 2020. Arduino Controlled Cooling Smart Footwear. (2020).

[26] Mariana Netto, Sarah Spurgeon, Anuradha Annaswamy, Sandra Hirche, Françoise Lamnabhi Lagarrigue, Wilfrid Perruquetti, and Tariq Samad. 2016. CPHS2016 Meeting Scope and Objectives. http://www.cphs2016.org/scope-topics/

[27] Rolf Nordahl, Stefania Serafin, Niels C. Nilsson, and Luca Turchet. 2012. Enhancing realism in virtual environments by simulating the audio-haptic sensation of walking on ground surfaces. In *2012 IEEE Virtual Reality Workshops (VRW)*. 73–74. doi:10.1109/VR.2012.6180888

[28] Kazi Kowshin Raihana, Md. Sabbir Hossain, Md. Tahsan Dewan, and Hasan U. Zaman. 2018. Auto-Moto Shoes: An Automated Walking Assistance for Arthritis Patients. In *2018 2nd International Conference on Electronics, Materials Engineering & Nano-Technology (IEMENTech)*. 1–8. doi:10.1109/IEMENTECH.2018.8465302

[29] Anil Raj and James Perry. 2000. Vibrotactile Displays for Improving Spatial Awareness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 44 (07 2000). doi:10.1177/154193120004400148

[30] Prabhav Nadipi Reddy, Glen Cooper, Andrew Weightman, Emma Hodson-Tole, and Neil Reeves. 2016. An in-shoe temperature measurement system for studying diabetic foot ulceration etiology: preliminary results with healthy participants. *Procedia cirp* 49 (2016), 153–156.

[31] Nihar Sabnis, Dennis Wittchen, Ata Otaran, Fatima Badmos, Siyi Liu, Aryan Saini, Georg Regal, Vincent van Rheden, Florian 'Floyd' Mueller, Suranga Nanayakkara, et al. 2025. Walking the Future: Bridging Foot Augmentation into Next Steps of Human Augmentation. In *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*. ACM, 1–7. doi:10.1145/3706599.3706742

[32] Aldo Sassi, Alessandro Stefanescu, Andrea Bosio, Marco Riggio, Ermanno Rampinini, et al. 2011. The cost of running on natural grass and artificial turf surfaces. *The Journal of Strength & Conditioning Research* 25, 3 (2011), 606–611.

[33] Ruben Schlonsak, T. Yang, Marco Torge Gabrecht, and Denys Jörg Christian Matthies. 2024. ShoeTect2.0: Real-time Activity Recognition using MobileNet CNN with Multisensory Smart Footwear. In *Proceedings of the 9th international Workshop on Sensor-Based Activity Recognition and Artificial Intelligence*. 1–5.

[34] Peter B. Shull, Haisheng Xia, Jesse M. Charlton, and Michael A. Hunt. 2021. Wearable Real-Time Haptic Biofeedback Foot Progression Angle Gait Modification to Assess Short-Term Retention and Cognitive Demand. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 29 (2021), 1858–1865. doi:10.1109/TNSRE.2021.3110202

[35] Paul Strohmeier, Seref Güngör, Luis Herres, Dennis Gudea, Bruno Fruchard, and Jürgen Steimle. 2020. BARefoot: Generating Virtual Materials Using Motion Coupled Vibration in Shoes. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 579–593. doi:10.1145/3379337.3415828

[36] Paul Strohmeier, Seref Güngör, Luis Herres, Dennis Gudea, Bruno Fruchard, and Jürgen Steimle. 2020. BARefoot: Generating virtual materials using motion coupled vibration in shoes. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. 579–593.

[37] Yuichiro Takeuchi. 2010. Gilded gait: reshaping the urban experience with augmented footsteps. In *Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology* (New York, New York, USA) *(UIST '10)*. Association for Computing Machinery, New York, NY, USA, 185–188. doi:10.1145/1866029.1866061

[38] Sales team. 2022. Digitsole® digital health company and leader in the e-health space. https://digitsole.com/

[39] Stryd Team. 2022. Running with Power. https://www.stryd.com/us/www.stryd.com/us/en/

[40] Chih-An Tsao, Tzu-Chun Wu, Hsin-Ruey Tsai, Tzu-Yun Wei, Fang-Ying Liao, Sean Chapman, and Bing-Yu Chen. 2022. Frictshoes: Providing multilevel nonuniform friction feedback on shoes in vr. *IEEE Transactions on Visualization and Computer Graphics* 28, 5 (2022), 2026–2036.

[41] Luca Turchet, Paolo Burelli, and Stefania Serafin. 2013. Haptic Feedback for Enhancing Realism of Walking Simulations. *IEEE Transactions on Haptics* 6, 1 (2013), 35–45. doi:10.1109/TOH.2012.51

[42] Keigo Ushiyama and Pedro Lopes. 2023. FeetThrough: Electrotactile Foot Interface that Preserves Real-World Sensations. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 10, 11 pages. doi:10.1145/3586183.3606808

[43] Ramiro Velázquez, Omar Bazán, Jorge Varona, Carlos Delgado-Mata, and Carlos A Gutiérrez. 2012. Insights into the capabilities of tactile-foot perception. *International Journal of Advanced Robotic Systems* 9, 5 (2012), 179.

[44] Yon Visell, Bruno L. Giordano, Guillaume Millet, and Jeremy R. Cooperstock. 2011. Vibration Influences Haptic Perception of Surface Compliance During Walking. *PLOS ONE* 6, 3 (03 2011), 1–11. doi:10.1371/journal.pone.0017697

[45] Yue Wang and Mark A Minor. 2014. Design of a bladder based elastomeric Smart Shoe for haptic terrain display. In *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 1236–1241.

[46] Yue Wang and Mark A. Minor. 2014. Design of a bladder based elastomeric Smart Shoe for haptic terrain display. In *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 1236–1241. doi:10.1109/IROS.2014.6942715

[47] Yue Wang, Takara E. Truong, Samuel W. Chesebrough, Pete Willemsen, K. Bo Foreman, Andrew S. Merryweather, John M. Hollerbach, and Mark A. Minor. 2021. Augmenting Virtual Reality Terrain Display with Smart Shoe Physical Rendering: A Pilot Study. *IEEE Transactions on Haptics* 14, 1 (2021), 174–187. doi:10.1109/TOH.2020.3029896

[48] Patrick Willnow, Max Sternitzke, Marco Torge Gabrecht, and Denys J.C. Matthies. 2024. SurfSole: Demonstrating Real-Time Surface Identification via Capacitive Sensing with Neural Networks. In *Proceedings of the 9th international Workshop on Sensor-Based Activity Recognition and Artificial Intelligence*. Springer, 1–9.

[49] wiseGEEK. 2022. What Is the Fastest Sense in Humans? http://www.thehealthboard.com/what-is-the-fastest-sense-in-humans.htm

[50] Jacob O Wobbrock and Julie A Kientz. 2016. Research contributions in human-computer interaction. *interactions* 23, 3 (2016), 38–44.

[51] Haisheng Xia, Jesse M. Charlton, Peter B. Shull, and Michael A. Hunt. 2020. Portable, automated foot progression angle gait modification via a proof-of-concept haptic feedback-sensorized shoe. *Journal of Biomechanics* 107 (2020), 109789. doi:10.1016/j.jbiomech.2020.109789

[52] Sijia Yi, Zhanyong Mei, Kamen Ivanov, Zijie Mei, Tong He, and Hui Zeng. 2024. Gait-based identification using wearable multimodal sensing and attention neural networks. *Sensors and Actuators A: Physical* 374 (2024), 115478.

[53] Yildiray Yildiz. 2020. Cyberphysical Human Systems: An Introduction to the Special Issue. *IEEE Control Systems Magazine* 40, 6 (2020), 26–28. doi:10.1109/MCS.2020.3025476

[54] LUO ZHI-FANG. 2009. Espacenet – Suchergebnisse. https://worldwide.espacenet.com/patent/search/family/044994912/publication/TW201038218A?q=TW201038218A

## Appendix

The following questionnaires were deployed:

(1) **State your Age, height, weight and shoe size.**
(2) **Whether the experimental shoes were the right size.**
- larger
- right size
- smaller

(3) **Whether the experimental shoes were comfortable.**
- comfortable
- generally comfortable
- not comfortable

(4) **Does the heel of the shoe often fall off.**
- always
- sometimes
- never

(5) **Whether the prototype fits the foot during running.**
- Does not fit, the bottom of the foot often hanging
- General fit, occasional overhang on the bottom of the foot
- Fit, no overhang on the bottom of the foot

(6) **Whether the sensation of vibration is obvious.**
- very obvious
- comparatively obvious
- generally obvious
- less obvious
- Very insignificant

(7) **Whether the feeling of cushioning is obvious.**
- very obvious
- comparatively obvious
- generally obvious
- less obvious
- Very insignificant

(8) **Whether you feel scared during the process of running blindfolded.**
- very scared
- general scared
- not scared

(9) **Whether you feel less able to balance (or have an unstable center of gravity) while running blindfolded.**
- always
- sometimes
- never

(10) **Other suggestions for smart insoles.**

QUESTIONNAIRE 2:

(1) **How similar is the grass simulated by the insole to the one in real life?**
- Very similar
- Similar
- Slightly similar
- Not similar

(2) **How much do you strain your lower muscles and ankle joints when running on simulated grass?**
- Very much
- Much
- moderate
- Little
- Very little

(3) **How similar is the sand simulated by the insole to the one in real life?**
- Very similar
- Similar
- Slightly similar
- Not similar

(4) **How much do you strain your lower muscles and ankle joints when running on simulated sand?**
- Very much
- Much
- moderate
- Little
- Very little

(5) **How similar is the asphalt simulated by the insole to the one in real life?**
- Very similar
- Similar
- Slightly similar
- Not similar

(6) **How much do you strain your lower muscles and ankle joints when running on simulated asphalt?**
- Very much
- Much
- moderate
- Little
- Very little

(7) **Please rank the strain of lower leg muscles and ankle joints in the three simulated terrains from largest to smallest.**
- Asphalt, sand, grass
- Asphalt, grass, sand
- Grass, sand, asphalt
- Grass, asphalt, sand
- Sand, grass, asphalt
- Sand, asphalt, grass

(8) **Which of the terrains simulated by this insole do you think is the most similar to the real one?**
- Sand
- Forest trail/Grass
- Asphalt

(9) **Which of the terrains simulated by this insole do you think is the least similar to the real one?**
- Sand
- Forest trail/Grass
- Asphalt

(10) **Did this 4D running system improve your experience compared to your usual treadmill workout at home? If the answer is "Yes", to what extent it has improved?**
- Yes
  - Significantly
  - Substantially
  - Moderately
  - Slightly
- No

(11) **Based on insole or VR application, briefly explain the shortcomings of this 4D running system and their corresponding measures that might improve the system.**