Prototyping Surface Slipperiness using Sole-Attached Textures during Haptic Walking in Virtual Reality

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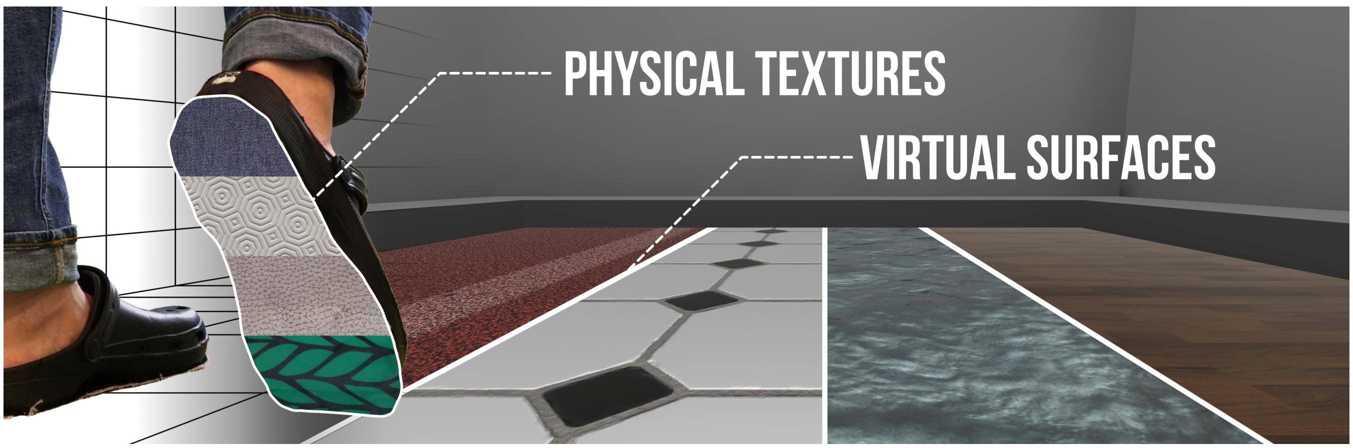

Figure 1: Using sole-attached material textures and virtual ground surfaces, we investigate the perception of slipperiness during haptic walking in Virtual Reality (VR) and their effect on the perceived realism of the experience.

ABSTRACT

Virtual Reality (VR) enables users to experience simulated environments, such as snowy or muddy landscapes. However, it remains challenging to communicate the tactile features of ground surfaces. Common approaches usually consist of bulky setups that are rarely able to simulate surface slipperiness, which is crucial for surface discrimination. Our work investigates physical surface textures attached underneath users' soles to translate mechanical friction into perceptual slipperiness during foot-based locomotion. To this aim, we selected a set of materials and classified them by their mechanical friction. In a study, we investigated their slipperiness perception underneath users' shoes during sitting and standing conditions. Our results show that measured differences in friction can inform the design of perceptual slipperiness. In a second study, we evaluated our sole-attached materials for experiencing different virtual surface environments. We show that perceived slipperiness during haptic walking in VR corresponded well to the visual slipperiness of different simulated environments.

CCS CONCEPTS

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

KEYWORDS

haptic walking, user studies, slipperiness simulation, haptic feedback, virtual reality

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1 INTRODUCTION

Virtual Reality (VR) allows users to experience compelling artificially generated worlds. While recent advancements have greatly improved the visual and auditory aspects of such systems, haptic technologies for stimulating the sense of touch still remain in their infancy. However, haptic feedback remains crucial in creating realistic and plausible virtual experiences wherein users can feel present and act accordingly [31].

Recent work has devoted much attention to investigating feedback mechanisms during hand-based interactions, such as simulating tactile surface features [5, 7, 10, 42] or influencing virtual weight perception [20, 47]. Providing feedback during natural foot-based locomotion can convey the natural properties and characteristics of the virtual surface environment and users' surroundings to enable effective navigation in VR [22]. Haptically supporting these rich sensations that are picked-up by our feet influences perceived realism and allows users to be fully immersed in the experience [2, 18, 22, 37, 40, 41, 43].

To simulate varying ground surfaces, research has investigated feedback applied to the user's feet during walking conditions. The presented systems can broadly be categorized in *tactile*, e.g., simulating sensations when stepping on cracking branches [37], and *kinesthetic*, for simulating changes in terrain, such as inclines or stairs [26, 46]. Yet, these approaches often require bulky actuators and sophisticated hardware to impose the required forces onto the human body. Since this is already a known issue for active haptic devices supporting hand interactions, it becomes even more challenging when considering the strength of our lower body. Consequently, there exists a clear need for inexpensive approaches that allow users to deliberately perceive differences in ground surface.

Our goal is to enable customization of haptic walking experiences through an iterative approach without the need of dedicated controller or devices. To achieve this, we look at simulating different levels of slipperiness, as slipperiness is a central aspect of how we experience ground surfaces. Moreover, slipperiness directly influences users' gait and remains highly important for virtual environments as mismatches between expected slipperiness of the virtual ground surface might lead to slipping or falling [21].

In our work, we investigate the use of material textures to simulate varying levels of slipperiness during haptic walking in VR. Rather than using active mechanisms, we propose an inexpensive passive approach, i.e., directly attaching material textures with different levels of friction underneath the shoe sole of the immersed user. To understand how this approach can enrich haptic walking in VR, we first needed to understand if physical friction of these materials translates to perceptual slipperiness. To this aim, we measured friction using a custom setup, such that we were able to identify and select a set of promising material textures. In a first psychophysical experiment, we were able to alter the perceived slipperiness based on the friction of the sole-attached material. Furthermore, we were interested in understanding if perceptual slipperiness of our sole-attached texture method would translate to different virtual environments with varying surface expectations. Therefore, in a second VR study, we used the most promising materials from the first experiment and displayed virtual ground surfaces, asking participants how well "what they see" matches "what they feel". We found that participants selected high matching rates for various virtual surfaces paired with our sole-attached materials, suggesting that this is an effective way to support haptic walking experiences. In this work, we make the following contributions:

(1) We show that friction of sole-attached material textures directly translates to distinct levels of perceived slipperiness;
(2) We demonstrate our approach for both walking and sitting experiences, regardless of participants' foot-dominance;
(3) We illustrate that sole-attached textures improve haptic walking experiences for different virtual surfaces.

2 RELATED WORK

2.1 Walking in Virtual Reality

During natural locomotion in VR, the user is bound by the limitations of the physical space surrounding them. Therefore, a naïve approach for navigating in virtual environments can cause harm to the user as they might bump into walls and physical objects. To address this, research has proposed different methods to enable the user to successfully move from one location to another [22].

Steinicke et al. [36] show how *redirected walking* can be used to suggest a larger virtual space than physically available. To achieve this, they unnoticeably offset the user's field of view, resulting in compensating behavior where they walk in a curve in the real world but visually continue to walk in a straight line. On the other hand, von Willich et al. [41] presented a set of locomotion techniques based on the 3D position of the user's feet and the pressure applied to the sole to navigate the virtual environment. *Virtual walking* is another common method where users walk "in place in the real world" [40]. Their motions are directly translated to moving in the virtual world [32]. The use of physical treadmills can enhance such navigation by allowing users to walk indefinitely, in any desired direction [18]. Such omnidirectional treadmills are finding their way into the consumer market, enabling body-centric travel.

Given the availability of such devices and the naturalness of human walking [22, 27], our approach investigates foot-based surface interactions to enhance the VR walking experience. We utilize a passive approach by augmenting shoe soles with physical materials.

2.2 Tactile Rendering During Walking

To ensure virtual environments provide a plausible and intuitive experience to the user, VR aims to replicate real-world sensations [31]. Here, haptic feedback remains crucial in creating experiences wherein users can feel present and act accordingly [35]. While much attention has been devoted to hand-based feedback, a holistic approach needs to be considered to ensure a sense of realism.

When walking in natural environments, we perceive the ground's physical features through our feet. Consequently, appropriate foot-based haptic feedback is essential to simulate natural and realistic haptic VR walking [8]. To this aim, research has investigated different methods to generate tactile experiences to users' feet. For example, *bARefoot* used embedded vibrotactile actuators for rendering ground-based interaction [37], while Wittchen et al. [43] extended this to include surface compliance. *Taclim*, a commercially available shoe outfitted with actuators, provides tactile feedback during haptic walking in VR [4]. Similar *haptic shoes* exist to provide haptic feedback for ground surface deformation [44], simulating stairs [26], or creating surface stickiness sensations [45].

An essential property of surfaces we walk on is the friction our feet generate with the floor material. Millet et al. [21] underline the importance of designing for slipperiness, as mismatches between expected friction of the virtual ground surface directly influence gait and therefore might cause slipping or falling. To this aim, Tsao et al. [38] use shoes with computer-controlled wheels to simulate slipperiness. They show that slipperiness is an essential tactile dimension to distinguish surface textures during walking. Furthermore, Deutsch et al. [8] investigate the use of a mobility simulator incorporating slipperiness. Their approach generates different haptic effects, such as icy or muddy surfaces, to investigate gait changes. However, these approaches remain bulky and rarely find their way to commodity VR.

Our work investigates haptic feedback during walking in VR. Specifically, we focus on simulating slipperiness with the aim of increasing realism. To this aim, we propose a lightweight technique to change perceived slipperiness—simply, by attaching commonly available material textures to soles.

2.3 Mixed Texture Perception

As our brain combines signals from different sensory channels, multisensory integration processes enable us to create a coherent perception. Here, different stimuli are weighted according to their reliability [9], which can result in scenarios where one sense can show dominance over another upon receiving mismatching information. Such effects have been used to influence a user's perception in visuo-haptic environments. A commonly used approach, called *pseudo-haptic* feedback, relies on visual dominance to create the impression of haptic feedback, and has been illustrated to simulate tactile experiences with virtual UI elements [34]. Similarly, visual distortion approaches are able to influence the perception of an object's properties such as weight [25], size [1], or function [12].

For material and texture perception, visuo-haptic integration has been used in psychophysical investigations to influence perceptual dimensions during tactile exploration [23]. For example, Hirano et al. [15] were interested in the effects of influencing hardness through visual stimulation. They found that users sensed different hardness levels by emphasizing the dent deformation of an overlaid virtual animation. Similarly, the perception of softness was influenced by augmenting visual cues when pressing a fixed object [24]. For the perception of materials, Iesaki et al. [16] superimposed virtual texture images on top of physical textures and concluded that although tactual impressions can be intentionally changed by providing appropriate visual stimulation, the coarseness of the visual and tactile textures have to be close to each other. These concepts have been integrated into different devices and controllers for providing more realistic surface texture feedback [6, 10, 42].

In this work, we investigate the visuo-haptic integration of visual ground textures and foot-based tactile feedback. Specifically, we use material textures with varying levels of friction attached to the user's shoe soles to simulate the sensation of slipperiness. As the visual and haptic information correspond, our approach enhances the realism of the virtual experience.

Figure 2: Our initial set of materials for measuring friction.

3 SOLE-ATTACHED MATERIALS FOR SIMULATING SURFACE SLIPPERINESS

The following section introduces our approach to define a set of material textures that are perceptually different in terms of slipperiness perception when attached to the sole of a shoe.

3.1 Material Selection

To study the use of material textures for slipperiness perception, we explored and collected a large assortment of materials with a wide range of friction.

For our initial set, we decided on 18 samples collected from different sources, including fabric sample books for commercially available sofas and home-decoration items such as tablecloths. The materials (M_0 through M_{17}) were selected based on their surface smoothness and material flexibility (see Figure 2).

To classify our set of materials, we assessed the coefficient of friction by measuring the displacement time of each material sliding a fixed distance over an inclined surface.

Our approach seeks to derive the coefficient of friction (μ) of an object sliding from point A to point B on an inclined plane. To this aim, we calculate the coefficient of friction by solving the equation derived from the conservation law of energy [30]. The mechanical energy of an object, which is the sum of its potential energy (E_p) and its kinetic energy (E_k), can be determined at both the initial time (t_i) and the final time (t_f) of the sliding process from the known weight, which is the multiplication of mass (m), gravitational force (g), position (H) and velocity (V) of the object. The difference, or loss in energy, is determined by the work done in sliding the object over the surface, equalling the frictional force (F_f) times the distance (d). By definition, the frictional force is equal to the coefficient of friction (μ) times the normal force (N) to the contact plane, giving

$$\mu = (mgH)/N - ((md)/2)/t^2 \quad (1)$$

As all parameters except the sliding time (t) are constant, this can be expressed as

$$\mu = a - b/t^2 \quad (2)$$

where a and b are constants.

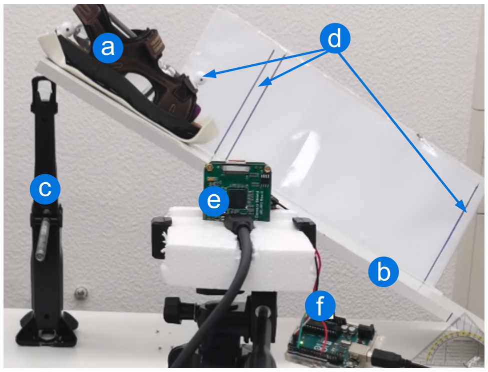


Figure 3: Our setup to measure friction. Here, a surface texture material, attached underneath the sole of a weighted sandal (a), slid over a smooth board (b) inclined by $30°$ (c). During movement, the marker on the sandal lined up with fixed markers (d) to be captured by a global shutter camera (e) connected to a microcontroller (f) at 60 fps.

3.2 Material Classification

Using our approach, we classified our materials by measuring their coefficient of friction. Rather than aiming at capturing highly accurate friction measurements, our goal was to order our set of materials in terms of friction using off-the-shelf hardware.

3.2.1 Apparatus. The setup, shown in Figure 3, consisted of a smooth board fixed to an inclination of 30 degrees. A backdrop with markers indicated the start and end of a fixed 37 cm distance. Each material was cut down to 11 cm by 26 cm, and attached underneath a sandal (EU 41) using fabric fastener (Velcro©). We compensated for minor weight differences between materials by adapting the amount of fabric fastener. To ensure each sandal would provide enough force for displacing, a 0.5 l water bottle was placed inside, resulting in a total weight 770 grams. A global shutter camera (OV9281) connected to an Arduino UNO was positioned facing the board and captured images at 60 fps.

3.2.2 Procedure. For each measurement, the sandal was placed on the top end of the board. Upon release, the sandal would slide down the board, with the total displacement time varying based on the friction between the material underneath the sandal and the board. The camera recorded the object's movement, with each frame embedding the recording timestamp. To measure sliding time, we calculated the difference between the timestamps of the frames where the sandal marker lined up with respectively the start and end marker. For each material, we repeated the same procedure 5 times and averaged the measurements to obtain the final result.

3.2.3 Results. The resulting measurements, depicted in Table 1, enabled us to classify our materials. To select a final set of materials varying in relative friction, we considered the average measured displacement time, the standard deviation of the measurements, and the capture rate of our camera setup. Specifically, the 60 fps camera setup provided us with 1 frame every 16.66 ms. Therefore, we determined that the displacement time should have a difference of at least 2 potential frames, i.e., 33.33 ms. This way, we ensured that the selected materials would provide sufficiently different friction coefficients. We selected M_0 as the texture providing the least amount of friction, followed by M_3, M_5, M_{12}, and M_{17}. While M_{17} did have a large standard deviation, the displacement time was significantly higher than M_{12} to compensate for both materials' standard deviation and the minimum required frame difference.

Table 1: The average displacement time (DT), standard deviation (SD) and the coefficient of friction (COF) of our materials (Mat). Shaded rows indicate materials selected for investigating perceptual slipperiness.

No	Mat	DT (ms)	SD (ms)	COF	No	Mat	DT (ms)	SD (ms)	COF
1	M_0	270	0.29	0.083	10	M_{16}	332	3.43	0.459
2	M_1	273	6.09	0.107	11	M_5	348	6.00	0.528
3	M_2	276	7.33	0.132	12	M_4	366	7.20	0.592
4	M_{14}	284	1.48	0.188	13	M_{10}	375	9.54	0.622
5	M_6	300	0.10	0.296	14	M_{12}	386	6.48	0.654
6	M_3	315	0.07	0.380	15	M_9	394	6.19	0.674
7	M_{15}	316	0.51	0.382	16	M_8	408	6.00	0.711
8	M_7	318	6.05	0.395	17	M_{11}	411	5.77	0.718
9	M_{13}	329	9.74	0.448	18	M_{17}	453	20.14	0.807

4 STUDY 1: SLIPPERINESS PERCEPTION OF SOLE-ATTACHED MATERIAL TEXTURES

We conducted a psychophysical experiment [19] to investigate whether the mechanical friction measurements, i.e., the differences in sliding time, of the sole-attached textures translate to perceptual differences in slipperiness. To collect more insights on our approach, we also studied potential differences caused by users' stances, i.e., sitting vs. walking, and effects relating to users' foot-dominance. Participants were given two shoes with (for them) unknown materials attached. We used a two-alternative forced choice (2AFC) procedure [12, 25, 36], in which participants were asked to identify the more slippery shoe by responding to the forced question "Which shoe felt more slippery", either with left or right.

4.1 Design

We used a within-subjects experimental design with a set of 5 different materials underneath the left and the right sole, resulting in a total of 15 combinations. For counterbalancing purposes, participants were assigned sequence numbers. The study consisted of two parts, sitting and walking. Each evenly numbered participant started with the sitting part, while unevenly numbered participants first performed the walking part. As we considered that perception may differ between feet, we iterated over all combinations twice. Each iteration mirrored the left-right position of the compared materials. For each iteration, we used experimental design tables according to the Balanced-Latin Square method to account for first-order carry-over effects [3].

4.2 Apparatus

The study setup consisted of two pieces of 260 x 60 x 1.9 cm wooden board. Participants were either seated in a chair during the seated condition or walked over the boards for the walking condition. The experimenter was positioned behind a cardboard separator through which participants received and returned shoes.

The selected materials were cut to fit underneath the sole of identical lightweight plastic sandals (EU 41). Each material was firmly affixed to the sole using fabric fastener, with no parts of the material visible from the top. We controlled the weight of each shoe by adapting the amount of fabric fastener used, with each weighing 126 grams. For 5 pairs, we attached material to both left and right shoes, resulting in a set of 10 shoes.

4.3 Participants

A total of 15 volunteers (1 female, 14 male) participated in our study. They were aged between 19 and 56 years old ($M = 30.16, SD = 7.28$), with a height ranging from 166 cm to 192 cm ($M = 175.96$, $SD = 7.34$), and a weight between 68 kg to 96 kg ($M = 82$, $SD = 6.21$). As our setup consisted of a fixed shoe setup, we preselected participants based on their shoe size. All participants indicated to have an EU shoe size of either 41 or 42. None of them indicated to suffer from any symptoms of a strained leg muscle, such as muscle pain or tenderness. A total of 13 participants indicated to be right-footed, determined by asking the question: "Which foot do you prefer to kick a ball" [13].

4.4 Procedure

Before starting the experiment, each participant signed a consent form and was briefed regarding the upcoming course of events. Afterwards, participants were asked to take off their shoes and socks, and were seated.

During the walking part, the experimenter selected the next pair of shoes, and placed them onto the cardboard surface next to the chair. Participants were then asked to put on the shoes and walk normally over the catwalk, from the beginning to the end. Upon completion, participants verbally indicated which shoe (left or right) was perceived to be more slippery, while the experimenter noted down their answer. Participants were asked to return to the chair, take off the shoes, and were handed the next pair.

In the sitting part of the experiment, the procedure was similar to the walking part but instead of walking over the catwalk, participants were asked to slide their feet forward and backward over the board 10 times while remaining seated. Afterwards, the participant indicated which shoe (left or right) they perceived to be more slippery, while the experimented noted down their answer.

Participants were unable to see the materials underneath the shoes to ensure their visual perception did not bias their assessments. Participants had short breaks after each trial, in which the experimenter changed the samples, a larger break between the sitting and standing condition, and additional breaks upon request. After the experiment, they completed a demographics questionnaire. The total study duration was about 40–50 minutes. Participants received candy as compensation for their participation in the study.

4.5 Results

The results of our study provided insights into the use of sole-attached material textures for perceiving slipperiness.

Our results indicate mechanical measurements translate to perceptual differences. To analyze the performance of our participants in identifying the more slippery material, we used the collected samples to fit the psychometric function modeling their discrimination performance [25, 36, 47]. We plotted the overall probability of our participants correctly identifying the more slippery material, i.e., responding either with left or right to the question "Which shoe felt more slippery" against M_0's sliding time differences to all other materials. We obtained the just-noticeable-difference (JND) [36], indicating when two materials differ in their perceived slipperiness (at 75% target probability), by fitting the quick function $F_Q(x; \alpha, \beta) = 1 - 2^{(-(\frac{x}{\alpha})^{\beta})}$ [19] to our sample distribution, optimizing for α and β. Materials below the JND are interpreted as indistinguishable from M_0 in terms of their slipperiness.

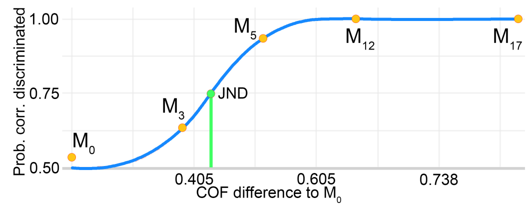


Figure 4: Discrimination results from perceptual experiment 1 plotted against the material sliding time differences to M_0 obtained from our mechanical measurement procedure.

overall % probability	M_0	M_3	M_5	M_{12}	M_{17}
M_0	0.47	63.5	93.25	100	100
M_3		48.3	70	91.75	100
M_5			43.3	85.5	100
M_{12}				50	96.5
M_{17}					51.7

Figure 5: Probability for correctly identifying the more slippery material. Comparison of discrimination performance.

With this, we demonstrate that a clear shift in perceived slipperiness occurred. This can be attributed to the sole-attached materials that differed in their sliding time. The plot in Figure 4 shows the *S-Curve* with materials above and below the JND, suggesting that our mechanical measurements translate to perceptual differences in slipperiness. M_0 approaches the expected 50% probably; here, the same material was attached to the shoes. This suggests that there was no difference caused by foot dominance or the preparation of the shoes and materials. Further, M_0 has a JND of .438 COF equating to 57 *ms*, meaning that materials ($\geq$ .438 COF) are perceived as less slippery. Here, M_5, M_{12} and M_{17} are perceptually different from M_0, whereas M_3 appears to be indistinguishable. To the best of our knowledge, we are the first to report a tangible relationship between the COF of sole-attached material textures and a shift in perceived slipperiness.

Moreover, we were interested in participants' discrimination performance, comparing all materials to each other. To do so, we computed the overall probability for correctly identifying the more slippery material and plotted the data in a confusion matrix, see Figure 5. Despite M_3 vs. M_5, all materials seem to differ substantially in terms of slipperiness, leading to high discrimination probabilities.

sitting/ walking	M_0	M_3	M_5	M_{12}	M_{17}
M_0	46.7 (W)	63.5	96.5	100	100
M_3	63.5	56.7 (W)	70	96.5	100
M_5	90	70	43.3 (W)	87	100
M_{12}	100	87	83.5	46.7 (W)	100
M_{17}	100	100	100	93	50 (W)

Figure 6: Probability for correctly identifying the more slippery material by splitting the data into walking and sitting.

left/ right	M_0	M_3	M_5	M_{12}	M_{17}
M_0	47 (L)	60	93	100	100
M_3	67	48.5 (L)	64	94	100
M_5	93.5	76.5	43 (L)	84	100
M_{12}	100	90	87	50 (L)	97
M_{17}	100	100	100	96.5	48.5 (L)

Figure 7: Probability for correctly identifying the more slippery material by splitting the data into left vs. right foot.

Additionally, we found that all materials approach the expected 50% probability, when being compared to themselves, with M_5 being on the edge of acceptable (43.3%). This provides further evidence for the validity of our physical measurement approach. To this end, we ran our analysis on all collected responses from our participants.

Our results show stance and foot-dominance does not influence slipperiness perception. We split the data into walking and sitting, and the same material being attached to the left and right shoe. Then, we re-ran the analysis above to identify potential differences in our collected sample. The results for walking vs. sitting are depicted in Figure 6 and left vs. right foot in Figure 7. Note that there appears to be no noticeable difference in discrimination performance. From this, we conclude that our results equally translate to both feet. This is an interesting finding, because it allows designers to create varying slipperiness sensations for each foot individually—expanding the practical slipperiness rendering capabilities of our approach.

Participants also correctly identified the relative slipperiness of sole-attached materials, regardless if they were walking normally or sliding their feet while seated. We even observed slightly better discrimination performance in favor of the seated experience, which is important, as nowadays many VR applications can be experienced while seated. Since our results show that participants accurately discriminated different sole-attached materials regardless of posture, our insights unlock a wide range of use cases.

To summarize, our study revealed that the physical measurements, i.e., differences in sliding time, of our materials translate to perceptual differences in slipperiness. Participants could reliably distinguish M_0, M_5, M_{12}, and M_{17} from each other, whereas M_3 was challenging to discriminate from M_0 and M_5 for participants. Furthermore, we could not identify any differences potentially caused by participants' foot-dominance or between sitting and walking experiences. To reduce the number of materials for our second experiment, we kept the materials M_0, M_5, M_{12}, and M_{17}.

5 STUDY 2: SLIPPERINESS SIMULATION DURING HAPTIC WALKING IN VR

We conducted a user study to understand if our approach was able to support different virtual floors during haptic walking in VR.

5.1 Apparatus

For our study, we used 4 pairs of shoes with perceptually different materials in terms of slipperiness, i.e., M_0, M_5, M_{12}, and M_{17}. The tip of each shoe was fitted with a custom-designed mount for attaching a tracker to register them with their virtual representation in VR. During the study, participants were seated in front of the floorboards from the first study. They could freely move their feet while remaining seated and used VR controllers to answer questions.

Our VR environment consisted of a neutral space in which we could alter the visual representation of the virtual floor. For the haptic baseline condition, the material of the floor was depicted as a neutral grey material. For other conditions, we selected 8 different terrains (T_1 through T_8) from the Unity Asset Store with different surface features which we expected to differ in their visual material slipperiness (Figure 2). Virtual shoes were represented with black formal shoes.

The environment was built in Unity 2019.4.30f1, while the in-situ surveys were created using the VRQuestionnaireToolkit [11]. Rendering was done using a HTC Vive Pro 2 headset connected to a desktop computer with an Intel i7 CPU, 16 GB RAM and an Nvidia GeForce GTX 980Ti graphics card. For safety reasons, we only considered the sitting condition for this study.

5.2 Participants

A total of 8 participants (all male), aged between 20 and 54 years old (M = 31.10, SD = 5.28), with backgrounds in Physics, Computer Science, Economics, and Sports Sciences volunteered for our study. Their body height ranged between 165 cm and 180 cm (M = 173.90, SD = 6.40), while their weight was between 68 kg and 88 kg (M = 79.55, SD = 5.10). Again, we preselected participants based on their shoe size. All participants had an EU shoe size ranging between 41 and 42. All participants confirmed that, to the best of their knowledge, they did not suffer from any condition influencing their gait, such as strained leg muscles. Furthermore, 3 participants reported never to have used VR technology before, while the other 5 indicated they had used VR before. The post-experiment SUS presence [33] scores (M = 4.93, SD = 1.33) suggested sufficient immersion of the virtual experience.

5.3 Procedure

Before starting the experiment, each participant provided signed consent and was briefed regarding the upcoming events. Participants were asked to take off their shoes and socks, seat themselves on the chair in front of the board, and put on the head-mounted display (HMD). To familiarize themselves with the VR controls, participants were given a short mock survey.

Our study consisted of two baseline phases and a mixed perception phase.

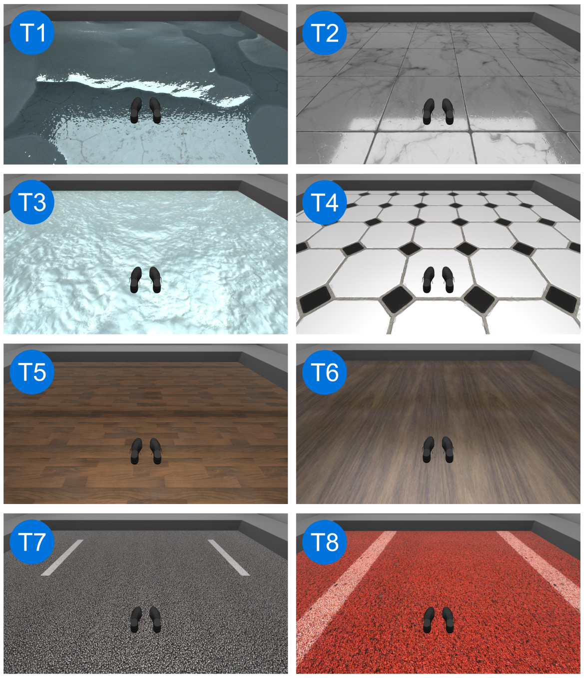


Figure 8: Virtual floor materials, with an icy surface and snow patches (T_1), a reflective tiled floor (T_2), snow (T_3), a matte tiled floor (T_4), a parquet floor (T_5), a smooth wooden floor (T_6), an asphalt surface (T_7), and a Tartan running track (T_8).

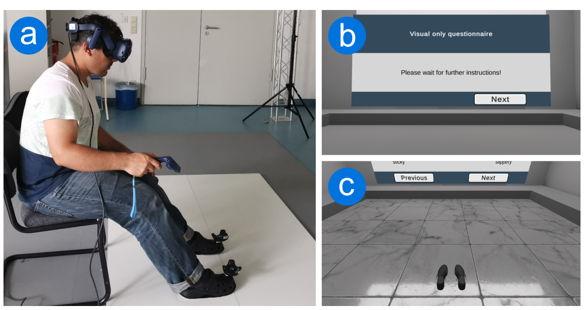


Figure 9: Our study setup where (a) the seated participant moved their feet over a smooth board to explore visuo-haptic slipperiness, as (b) a questionnaire guided them through the study and (c) the visual material of the floor changed.

In the haptic baseline phase, we assessed the haptic slipperiness of each pair without the presence of visual information. For each pair, the experimenter prepared the pair by placing the shoes in front of the participant. The participant was then asked to put on the shoes and freely interact with the floor by sliding their feet over the surface for a maximum duration of 10 seconds. They were then asked to rate the slipperiness of the floor on a 9-point Likert scale ranging from 1 (= meaning not slippery at all) to 9 (= extremely slippery). After responding to the questions, the participant was asked to take off the shoes as the experimenter prepared the next pair for evaluation.

In the visual baseline phase, we assessed the visual slipperiness of each virtual texture without the presence of haptic information. While not wearing shoes, the participant was presented with a different virtual floor texture. For each visual material, they rated the visual slipperiness of the floor on a 9-point Likert scale from 1 (= meaning not slippery at all) to 9 (= extremely slippery). They additionally were asked to identify the material of the virtual floor. Afterwards, the virtual floor changed to depict the next material for evaluation.

During the mixed perception assessment, we assessed the matching for all visual and haptic combinations of the virtual floor representations and the physical sole-attached textures. Each combination was only tested once to keep the total number of comparisons at a reasonable level. The experimenter prepared the respective shoe pair by placing them in front of the participant. As the participant put on the shoes, the virtual floor presented a different virtual texture. Participants were asked to freely slide their feet over the surface for a maximum of 10 seconds. Inspired by Degraen et al. [7]'s study, we formulated the following questions:

(1) Please compare how slippery the floor feels to how slippery the floor looks.
(−10 = looks too slippery, 0 = equal, 10 = feels too slippery)
(2) Please rate the realism level of the experience.
(1 = not realistic at all, 9 = highly realistic)

After responding to the questions, the participant removed the shoes, the experimenter prepared the next pair, and the virtual floor visually changed to the next material for evaluation.

After the experiment, participants completed two post-study questionnaires. One inquired about their demographics, and the SUS presence questionnaire [33] recorded the experienced presence in the virtual environment. Breaks were issued between each of the study phases, or upon the participant's request.

For each participant, the total study duration was about 1 hour. Participants received candy for their participation.

5.4 Design

We used a within-subjects experimental design consisting of two baseline phases, i.e., the haptic perception of the sole-attached materials and the visual perception of the virtual floor textures, and a main phase in which we assessed all visual-haptic combinations.

To balance for first-order carry-over effects, we constructed experimental design tables according to the Balanced-Latin Square method [3]. Here, we counterbalanced the study phases, i.e., haptic, visual and mixed perception ($n = 3$), and the individual assessments within each phase. For the haptic baseline phase, we considered the shoe pairs with different attached textures onto the sole ($n = 4$). For the visual baseline phase, we considered the virtual surface materials ($n = 8$). Lastly, for the mixed perception phase, we considered all combinations of shoe pairs and virtual textures ($n = 32$).

5.5 Results

Our results provide insights into the effect of sole-attached materials varying in slipperiness on the perception of realism and users' interpretation of the match between visual and haptic stimuli.

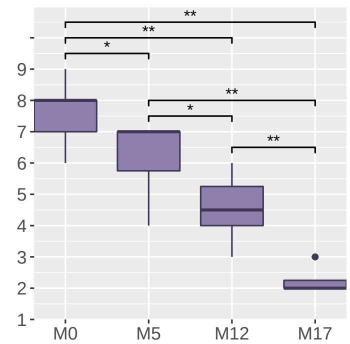


Figure 10: Box plots depicting the slipperiness ratings for the haptic baseline. Brackets connect groups with statistically significant differences (*, $p < .05$; **, $p < .01$).

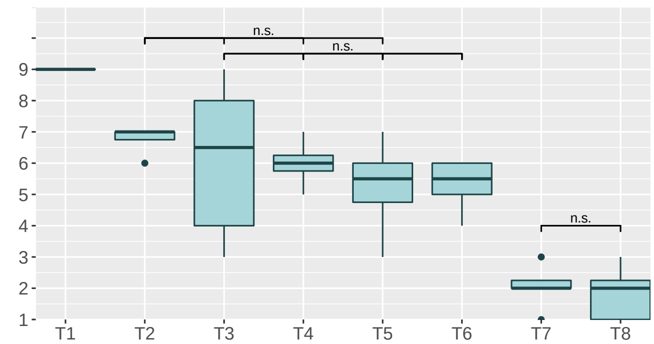


Figure 11: Box plots depicting the slipperiness ratings for the visual baseline. Brackets connect groups that did not show statistically significant differences, while all other comparisons were significantly different (T_1 compared to T_3, $p < .05$; T_1 compared to all others, $p < .01$, all other comparisons, $p < .05$).

5.5.1 Baseline Results. Participants' assessments of both baselines allowed us to test our initial assumptions about the perception of each physical sole-attached material and each virtual floor texture. We distinguish between the perception of slipperiness for *the haptic ratings of sole-attached textures* without visual information and *the visual ratings of virtual textures* without haptic information. For each case, we conducted a Friedman test with post-hoc analysis using Wilcoxon signed-ranks tests and Bonferroni-Holm correction.

The results of the haptic baseline ratings reveal that our selected set of materials communicated different levels of slipperiness. The ratings of slipperiness significantly differed depending on the type of material underneath the shoe sole ($\chi^2(3) = 22.269$, $p < .001$). Pair-wise analysis of perceived slipperiness showed a significant difference between all sole-attached materials (between M_0 and M_5, $p < .05$; all other comparisons, $p < .01$). The ratings with their significant differences are shown in Figure 10.

Moreover, we noticed a general downward trend from M_0 to M_5 to M_{12} and to M_{17}. This builds upon the results from study 1, and indicates that participants clearly perceived each material's slipperiness differently without the presence of visual information.

The results of the visual baseline ratings show that our set of virtual materials was divided into groups of visual slipperiness. Depending on the virtual floor texture presented, visual slipperiness was found to differ significantly ($\chi^2(7) = 46.827$, $p < .001$). Pair-wise analysis showed a significant difference between 18 comparisons (T_1 compared to T_3, $p < .05$; T_1 compared to all others, $p < .01$, all other comparisons, $p < .05$). The ratings are shown in Figure 11 with brackets indicating only non-significant results for readability. All not shown comparisons are significant.

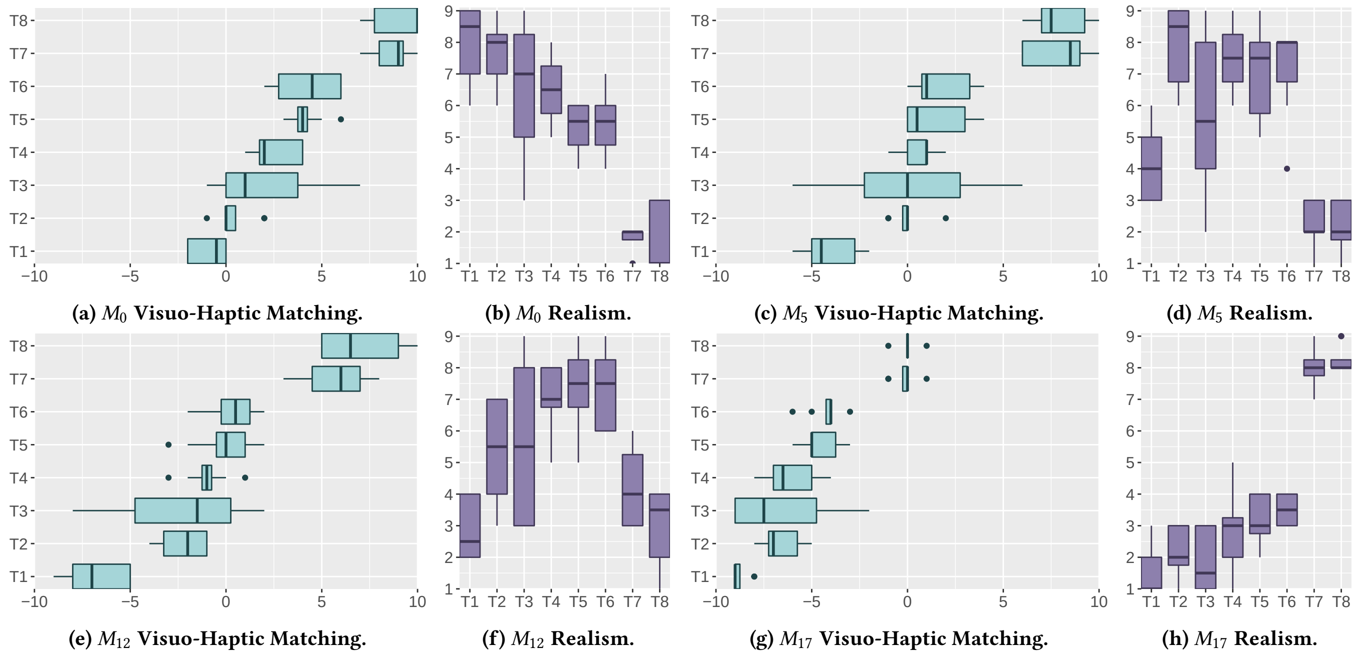
When asked which material each visual surface texture represented, all participants correctly recognized the textures T_1 as an ice surface, T_4 as a tiled floor, and T_7 as asphalt. For the textures T_5 and T_6, all mentioned materials referred to wood-like surfaces, e.g., laminate, parquet, or wood. For T_2, 1 participant mentioned ceramic while all other indications (7) were tiled floor, with 2 emphasizing a wet tile, and 1 stating a slippery tile. For T_8, 6 participants indicated to perceive tartan, while 2 mentioned some type of artificial carpet. The texture of T_3 was recognized as snow by half of the participants (4), while others indicated marble (1), ice (1), or flour (1). One participant was unable to assign any material to T_3.

The visual ice surface of T_1 was considered to be extremely slippery, while on the opposite side of the spectrum, T_7 (asphalt) and T_8 (tartan) provided the impression of surfaces lacking any slipperiness, i.e., rough surfaces with grip. The materials depicted by T_2 (wet tiles), T_3 (snow), T_4 (dry tiles), T_5 (parquet), and T_6 (wood) were considered to be a medium-high level of slipperiness.

5.5.2 Mixed Perception Results. Using the assessments of combinations of physical sole-attached materials and virtual floor textures, we assessed their mixed visuo-haptic experience. We were interested in understanding which physical material best communicated with which virtual texture. Our analysis considers each combination's *the visuo-haptic matching rate* and *the correlation between visuo-haptic matching and realism*, the latter shown in Figure 12.

From the ratings of the visuo-haptic match, we conclude that different sole-attached material textures were found to better fit different visual textures. We analyzed the ratings of the visuo-haptic match between each material and each visual texture and their respective realism ratings. We conducted Friedman test with post-hoc analysis using Wilcoxon signed-ranks tests and Bonferroni-Holm correction.

For M_0, the visual textures T_1, T_2, and to a lesser degree T_3 were rated to match the physical texture best. A significant difference in matching rate between T_1 and T_4 ($p < .05$) indicated that for other combinations, perceptual slipperiness was found to be higher compared to the visual representation. For M_5, T_2 through T_6 provided representative matches to the physical stimulus, with T_5 and T_6 slightly leaning to look less slippery than the material felt. Here, T_1 compared to T_2 was found to visually look significantly more slippery than the material felt ($p < .05$), while T_7 and T_8 looked significantly less slippery than T_6 ($p < .05$). For M_{12}, again T_2 through T_6 provided representative matches to the physical stimulus, while T_2, T_3, and T_4 slightly leaned to look more slippery than the material felt. Here, T_1 compared to T_2 was found to visually look significantly more slippery than the material felt ($p < .05$), while T_7 and T_8 were rated to look significantly less slippery than T_6 ($p < .05$). For M_{12}, a



(a) M_0 **Visuo-Haptic Matching.** (b) M_0 **Realism.** (c) M_5 **Visuo-Haptic Matching.** (d) M_5 **Realism.**

(e) M_{12} **Visuo-Haptic Matching.** (f) M_{12} **Realism.** (g) M_{17} **Visuo-Haptic Matching.** (h) M_{17} **Realism.**

Figure 12: Visuo-haptic matching and realism rates per visual surface texture for each physical material. Here, the matching rates (a, c, e, g) are scaled from -10 **(= looks too slippery) to** $+10$ **(= feels too slippery), with** 0 **indicating a perfect match between the visual and haptic information presented. The realism rates (b, d, f, h) are scaled** 1 **(= not realistic at all) to** 9 **(= highly realistic).**

clear match was found with T_7 and T_8, while all other visual textures looked significantly more slippery (T_7 compared to T_6, $p < .05$).

Furthermore, we conclude that a perceived match between the visual and haptic stimuli was associated with a higher sense of realism for the virtual experience. We analyzed the correlation between the visuo-haptic matching ratings and the ratings of realism for each combination. For this, we converted the matching rates to their absolute values and inverted them. The matching ratings, on a scale from 0 (= visuo-haptic mismatch) to 10 (= visuo-haptic correspondence), were compared to the realism ratings (1 to 9) using Spearman's rank-order correlation, which indicated a significant and strong, positive correlation ($M_r = 0.93$, $p < .001$).

6 DISCUSSION

Designing realistic haptic experiences remains a challenging task. The field of haptic design underlines there is a lack of prototyping methods for creating effective haptic feedback [28], while additionally noting the importance of supporting end-user personalization [29]. Rather than relying on active devices, our use of surface textiles supports both end-users and professionals to design and customize their own experiences. Hereby, designers can utilize friction measurements that support perceptually varying feedback for simulating different surface environments.

Does physical friction correlate to perceptual slipperiness? From our results, we observed that attaching different textures to the sole of users' shoes is able to influence the perception of slipperiness. Starting from a wide range of materials, we first captured their coefficient of friction in section 3. In section 4, a user study with a subset of these materials revealed that the physical measurements correlate to perceptually different levels of slipperiness when attached underneath a shoe sole. These results hold true for walking and seated interaction, while footedness did not influence perception. Moreover, during the haptic baseline assessment in section 5, we observed that the selected materials continued to simulate significantly different levels of slipperiness when assessed individually.

Our insights show that surface materials can be used to prototype surface slipperiness. Rather than relying on active mechanisms, designers can rely on commonly available materials. This can benefit a wide range of application scenarios, e.g., friction-controlled rehabilitation of balance and mobility [21].

Does slipperiness simulation increase realism? Using sole-attached material textures, our study examined the relationship between users' perceived realism of the virtual experience and the matching rate between visual and haptic stimuli. We found a significant positive correlation between these factors, as demonstrated by our mixed perception evaluation in section 5. As participants rated the match between physical materials attached to their shoe soles and virtual ground surfaces, we observed that different combinations of materials provided a better match for different virtual surfaces. This correspondence was reflected in similarities in participants' perceived slipperiness. Additionally, we found that when haptic slipperiness was altered, the visuo-haptic match followed in the same direction, while realism decreased for mismatching information. While we did not evaluate realism for cases without haptic information, previous research suggests that the addition of feedback improves the user's experience [17].

Our insights show that perceptual slipperiness is crucial in enabling realism in virtual walking scenarios. Foot-based locomotion can therefore benefit from the addition of sole-attached materials that match the visual floor textures. An interesting future approach can investigate how the increased realism enables more natural walking in a wide range of VR experiences.

What are potential applications for Haptic Walking? As haptic feedback research expands, these technologies will increasingly enhance the plausibility of user experiences. Our lightweight approach can improve various foot-based navigation methods and be applied to different haptic walking applications.

A key finding from our studies is that stance minimally affects the perception of slipperiness. This makes sole-attached material textures versatile for both seated and standing VR experiences. Additionally, footedness did not influence slipperiness perception, offering a controllable method for simulating environmental surfaces. We are excited to explore slipperiness for each foot independently, potentially supporting novel redirected walking methods.

Furthermore, our method provides an affordable way to vary slipperiness perception during haptic walking. Since it doesn't rely on active mechanisms and can be applied to any shoe, it complements other methods like omnidirectional treadmills for VR. Integrating vibrotactile actuation in the shoe sole can enhance feedback throughout the walking movement and simulate complex surface interactions. Additionally, auditive feedback during footsteps can create multimodal surface experiences.

6.1 Limitations & Future Work

Our work does not remain without its limitations. One major issue was the fixed shoe size used in our studies, leading to a gender imbalance among participants. Future work should include different sizes, either through a range of fixed shoes or an adaptive approach.

Furthermore, our current focus was on using sole-attached textiles to communicate slipperiness, investigating if friction measurements correlate with perceived slipperiness. Future research should explore dynamically changing shoe textures, possibly using a method similar to the *HapticRevolver* [42] to alternate between textures and dynamically influence slipperiness perception.

Additionally, our work only addressed reduced friction for slipperiness. Natural interactions also involve increased friction, or stickiness, as seen in *walking on snow* [45]. Future approaches should explore adhesive materials during walking, which would also require adjustments to the friction measurement method since sticky materials don't slide easily on an inclined plane.

Lastly, we used commercially available textures and measured their coefficients of friction to relate to perceived slipperiness. Future work could investigate other materials to control foot-based friction, including digital fabrication methods to create surfaces with specific features. This aligns with related research on designing tactile experiences that users can fabricate on demand [5, 7, 10, 14, 39]. Applying these methods to foot-based interfaces can enable controlled foot-based tactile experiences in virtual environments.

7 CONCLUSION

In this work, we introduced a novel method for prototyping haptic walking experiences in VR by attaching readily available material textures to shoe soles, simulating different levels of slipperiness. We first categorized our materials based on physical friction, identifying 5 promising materials out of 18. Our first experiment demonstrated a relationship between mechanical friction and perceived slipperiness, irrespective of stance or footedness. In a second study, we tested these materials in a virtual environment, assessing the matching rate between visual and haptic stimuli and evaluating realism. Results showed high matching rates for specific combinations while enhancing realism. This technique offers designers an inexpensive way to prototype realistic foot-based surface interactions, providing valuable insights for designing haptic walking experiences. In future work, we aim to dynamically influence slipperiness by using methods to alternate between textures [42] or by fabricating surfaces with controlled surface friction [5, 7, 10, 14, 39].

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