Digitally Fabricated Sole-Attached Textures for Haptic Walking in Virtual Reality

Donald Degraen
donald.degraen@canterbury.ac.nz
HIT Lab NZ
University of Canterbury
Christchurch, New Zealand

Stephan Lukosch
stephan.lokusch@canterbury.ac.nz
HIT Lab NZ
University of Canterbury
Christchurch, New Zealand

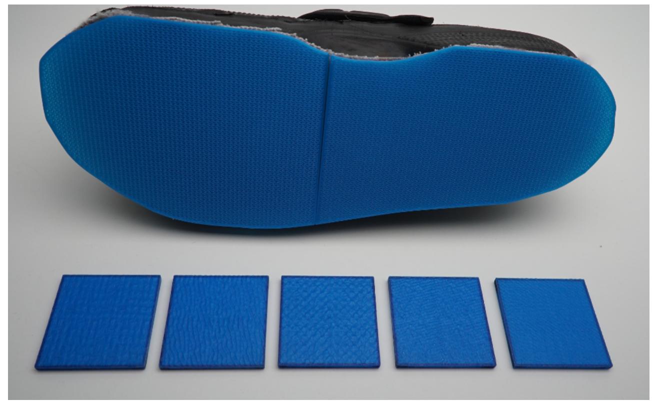

Figure 1: Fabricated sole-attached textures. Here, the texture applied underneath the shoe sole was 3D-printed using an infill-based additive manufacturing method, while the bottom textures illustrate different potential surface features that can be designed to control surface roughness [8].

Abstract

Haptic feedback is essential for creating immersive and realistic Virtual Reality (VR) experiences, yet current foot-based haptic systems often rely on bulky and expensive hardware. Our previous work explored sole-attached textures to simulate different ground surfaces, allowing users to perceive changes in terrain through passive haptic feedback. To enable controlled variations in friction, we propose to enhance our approach by leveraging digital fabrication techniques. Digitally fabricated sole-attached textures present an accessible, lightweight, and cost-effective method for enhancing foot-based interactions. We discuss the potential of this technique for different applications, as well as future directions for optimizing fabrication of materials, design approaches, and multimodal integration. Our work contributes to the growing field of haptic design by demonstrating how customized, 3D-printed artifacts can enrich virtual experiences.

CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; Virtual reality.

Keywords

haptic walking, haptic feedback, virtual reality, personal fabrication, digital fabrication, 3D printing

ACM Reference Format:
Donald Degraen and Stephan Lukosch. 2025. Digitally Fabricated Sole-Attached Textures for Haptic Walking in Virtual Reality. In *Workshop on Walking the Future (WTF '25), April 27, 2025, Yokohama, Japan.* ACM, New York, NY, USA, 3 pages.

1 Introduction

Virtual Reality (VR) enables users to experience a wide range of simulated environments, such as snowy or muddy landscapes. While walking in such virtual experiences, generating realistic and plausible foot-based haptic feedback is crucial to ensure users feel present and act accordingly [26]. However, communicating the diverse tactile features of different ground surfaces remains challenging.

In recent years, a wide range of foot interfaces have been proposed to simulate haptic walking. These systems can broadly be categorized into *tactile*, for simulating detailed sensations, such as stepping on crackling leaves [28], and *kinesthetic* approaches, for simulating changes in terrain, such as inclines or stairs [23]. Sadly such interfaces often require bulky actuators and sophisticated hardware to impose the required forces onto the human body, making them inaccessible to end-users of off-the-shelf VR setups.

Our work addresses the need for inexpensive and accessible approaches to allow users to deliberately perceive differences in ground surfaces during haptic walking. Our initial investigation proposed physical surface textures attached underneath users' soles to translate mechanical friction into perceptual slipperiness during foot-based locomotion [6]. While this enabled us to enrich foot-based haptic feedback, our method remained dependent on the physical friction properties of commercially available textures. Informed by research on designing tactile experiences that users can fabricate on demand [8, 11, 13, 14, 31], we aim to create surfaces with desired features using digital fabrication technologies. This will enable us to extend the gamut of 3D-printed friction by creating controlled foot-based tactile experiences for virtual environments.

2 Digitally Fabricated Foot Augmentations

Sole-attached textures provide a lightweight approach to augment foot-based interfaces. The strength of this approach lies with controlled fabrication of surface textures to vary physical friction. We discuss several pathways to enhance our approach in future work.

2.1 Sole-Attached Textures

Our recent work pointed out that sole-attached textures can be used to simulate ground features in virtual environments [6]. To do so, we used commercially available textures from a wide range of sources, including fabric sample books. Using these samples, we took physical measurements to determine their coefficient of friction. In human-factor experiments, we related physical friction to perceptual slipperiness. By attaching our textures to the sole of users' shoes, we showed that perceived slipperiness during haptic walking in VR corresponded well to the visual slipperiness of different simulated environments.

Our work was motivated by passive haptic feedback for VR [15]. The feedback provided by passive interfaces, e.g., physical materials [9] or everyday objects [4, 5, 19], has been shown to significantly enhance the realism of virtual experiences. A key part lies with successful integration of visuo-haptic stimuli [30], i.e., a combination of visual ground textures to communicate varying levels of visual friction and foot-based feedback to provide haptic friction.

2.2 Fabricating Slipperiness

An exciting route for future work lies with investigating different materials to control sole-based friction. One example includes the use of digital fabrication methods to create textures with controlled surface features. As pointed out by related work [8, 11–14, 31], the design of such objects can support tactile experiences which can be fabricated by the user on demand. As illustrated in Figure 1, applying these methods to foot-based interfaces can enable controlled fabrication for foot-based tactile experiences.

The tactile response of an object depends on its geometry, material, and the manufacturing process. Therefore, we need to carefully select physical features to haptically convey surface features and ensure designs remain inclusive and accessible for all users. To achieve desired experiences, computational design can be implemented to model physical interactions [2], haptic reproduction can be used to reproduce real world impressions [16], and perceptual modeling techniques can predict users' touch perception [21]. The latter approach will be essential to understand how a given design will be perceived prior to fabrication.

2.3 Haptic Aesthetics

To support designers in creating custom experiences through controlled fabrication of underfoot materials, haptic designers require intuitive approaches to support them in their design workflows [24]. While recent work has investigated different design approaches for vibrotactile feedback [7, 33, 34], design approaches for enhancing virtual experiences with physical materials remain underexplored [9]. Therefore, an open challenge lies with design tools for creating 3D-printed objects with desired haptics. These tools should take desired tactile qualities as input and generate the corresponding design and printing parameters as output to enable designers to design haptic aesthetics (cfr. visual aesthetics).

Furthermore, digital fabrication of sole-attached materials supports end-user customization and personalization, both crucial aspects of haptic experience design [25]. By modifying digital designs to users' individual sensitivities prior to fabrication, haptic experiences can be optimized to the user in question. Future research could explore different parameters of haptic personalization tools to provide intuitive ways for users to calibrate the feedback provided and enable them to define their own interactions [10].

2.4 Multimodal Integration

Sole-attached textures for haptic walking provide a lightweight and affordable approach to vary the perception of surface slipperiness. As this does not use any active mechanisms, and the used material textures can be applied to any existing shoe, this approach can easily complement other methods, such as omnidirectional treadmills for body-centric walking in VR. Moreover, by integrating vibrotactile actuation inside the shoe sole, different feedback mechanisms can be combined during the entire walking movement [28], enabling the simulation of more complex surface interactions.Considering recent advancements in vibrotactile actuation, sole-attached materials can be enhanced with simulated forces [22] or sensory substitution approaches providing directional cues [32]. Analogously, during the footstep experience, auditive feedback can be used to generate multimodal surface experiences [29].

2.5 Applications

The history of sports goes back several thousands of years. Sports started off as preparation for war or training as hunter. Virtual reality is, e.g., used for sensorimotor training [1], improving motor performance [3], or mental imagery training [35]. Augmented reality is, e.g., used to provide augmented feedback [20] and various training and education scenarios [27]. Superhuman Sports [17, 18] relies on these technologies and focuses on augmenting sports to enhance a player's senses, to extend a player's body, augment the sports field, create new sports or enhance the training while making us experience superhuman capabilities. Following up on the multimodal integration with treadmills, such foot-based haptic feedback could be used to create superhuman sports that make athletes experience realistic sensations of different terrains, such as snowy or muddy landscapes, when training on a treadmill while preparing for diverse environments. Further, being able to simulate different haptic sensations, e.g., stepping on crackling leaves or changes with regard to the slipperiness of terrain, in combination with visuo-haptic experiences [30] could make virtual training sessions on a treadmill more engaging and effective.

3 Conclusion

Our work explores the potential of digitally fabricated sole-attached textures to enhance foot-based experiences. By leveraging 3D printing, custom surface textures can be created to modulate friction and simulate ground conditions, offering an accessible and lightweight alternative to traditional haptic feedback during haptic walking. We proposed directions for future research, including refinements of the design and fabrication processes to improve user customization and personalization and ensuring a wider range of tactile sensations. Additionally, integration with multimodal feedback mechanisms, such as vibrotactile actuation and auditory cues, could further enhance realism in virtual environments. Continued exploration of fabrication methods, material properties, and user-centered design principles will be essential in realizing the full potential of our approach.

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