# bARefoot: Generating Virtual Materials using Motion Coupled Vibration in Shoes

**Paul Strohmeier[1], Seref Güngör[2], Luis Herres[3], Dennis Gudea[4], Bruno Fruchard[1], Jürgen Steimle[1]**
Saarland University, Saarland Informatics Campus
Saarbrücken, Germany
[1]{*lastname*}@cs.uni-saarland.de, {*s8seguen*[2], *s8lsherr*[3], *s8degude*[4]}@stud.uni-saarland.de

## ABSTRACT
Many features of materials can be experienced through tactile cues, even using one's feet. For example, one can easily distinguish between moss and stone without looking at the ground. However, this type of material experience is largely not supported in AR and VR applications. We present *bARefoot*, a prototype shoe providing tactile impulses tightly coupled to motor actions. This enables generating virtual material experiences such as compliance, elasticity, or friction. To explore the parameter space of such sensorimotor coupled vibrations, we present a design tool enabling rapid design of virtual materials. We report initial explorations to increase understanding of how parameters can be optimized for generating compliance, and to examine the effect of dynamic parameters on material experiences. Finally, we present a series of use cases that demonstrate the potential of *bARefoot* for VR and AR.

### Author Keywords
haptic feedback, virtual reality, augmented reality, haptic rendering, material experiences, wearable computing, shoes, body-based interaction

### CCS Concepts
•**Human-centered computing** → **Haptic devices;** *Human computer interaction (HCI);* Empirical studies in HCI;

## INTRODUCTION
We experience the world through a sensorimotor loop; to evaluate the fragility of a thin sheet of ice, for instance, one might gradually apply force to it with one foot, while balancing on the other. The ice surface might react to this continuous action with small cracks. The tactile impulses from cracks correspond precisely to changes in pressure and provide an experience of the ice's structure and compliance. This whole process relies on the tight coupling of actions to sensory feedback of the resulting effects.

Previous work on haptic shoes provides compelling experiences such as changing the friction of the surface one is walking on [41], stepping up on to, and down from virtual objects [55], or even making the wearer feel as though they are walking on different textures [75]. However, none of these systems are designed to engage directly with the sensorimotor process.

We, therefore, present *bARefoot*, a vibrotactile shoe prototype with high-frequency sensing and vibrotactile actuation. *bARefoot* closely synchronizes vibration with user actions to create virtual materials. bARefoot can be used to (a) deepen the sense of immersion in VR by, for example, allowing users to probe the strength of a thin ice layer, or feel grass leaves against their shoe when walking in grass. It can be used in (b) AR for augmenting existing materials with additional haptic cues, for example, to subtly indicate a desirable direction to walk towards or make running on artificial grounds more enjoyable. Also, it can be used to (c) expand the user's perceptual horizon by providing embodied experiences of supplemental environmental information. For example, the level of air pollution might be conveyed as friction in the air [68].

We provide reflections on the implementation of systems which engage directly with the sensorimotor process, as well as a concrete implementation of a functional prototype. The prototype – *bARefoot* – has a high update rate adequate for tight sensorimotor coupling. The prototype has a separate control loop for perceptive acts and deliberate acts that allows deployment of high-resolution virtual materials, even in AR environments with poor position sensing. We complement the prototype with *vibrAteRial*, a design tool for creating and sharing virtual materials.

We use *bARefoot* and *vibrAteRial* for exploring the parameter space of virtual material experiences. We demonstrate that the virtual compliance illusion, as described for handheld devices [23, 34], also works for feet. We highlight that there are interactions between the number of grains used and the frequency of each grain in assessing the salience of the illusion, and that there appears to be a maximum virtual depth which can be achieved, above which the salience of the illusion is reduced. We also highlight the utility of non-static parameters for generating a variety of experiences and present four compliant materials created with *vibrAteRial*. Finally, we present use cases of how *bARefoot* might be used in Virtual and Augmented Reality settings.


**UIST '20, October 20–23, 2020, Virtual Event, USA**

ACM ISBN 978-1-4503-7514-6/20/10.
http://dx.doi.org/10.1145/3379337.3415828

## RELATED WORK

Here we discuss haptic perception – highlighting that tight sensorimotor coupling is required for most material experiences – and examples of devices that use such coupling. We then discuss work on haptic shoes, virtual compliance, design tools, and design to contextualize our contributions.

### Active Perception & Haptic Rendering Devices

When lifting an object, the fingertips continuously react and adapt to its material properties. Tangential force in reaction to lifting the object provides information about an object's weight [31]. Finger deformation in reaction to applied force is used to infer compliance [10]. Vibrations caused by micro-movements over the surface of the object create an experience of texture [9]. These material experiences are generally mediated by pacinian corpuscles, which are nerve endings in the skin sensitive to vibration [8]. Consequently, many of these experiences can be rendered by providing tactile impulses, closely coupled to human actions [68].

Systems based on tight coupling between actions and corresponding tactile impulses have been used in haptics research. Examples include a haptic controller by Yao et al. which is vibrated in such a way that a rolling stone inside the controller is experienced [89], or moving a pen over a flat surface which provides the experience of a pre-recorded texture through vibration [12, 53]. The experience of texture, however, does not require such recordings – simple grain-based, parametric approaches have also shown success [70].

This approach is finding application in HCI and VR research. For example, Heo presented a VR controller which provides the experience as if it was bent or twisted, by providing grain-based feedback relative to the force exerted on it [23]. Lee et al. presented TORC, a device that supports high dexterity finger interactions with virtual objects [36]. Siu demonstrates similar principles in a VR controller which allows blind users to explore VR with a cane [66]. Haptic feedback with tight sensorimotor loops is not limited to VR devices. For example, ReFlex, a bendable smartphone, augments the bending experience with motion-coupled feedback [69].

### Haptic Rendering and Haptic Shoes

Studies of pacinian corpuscles in human feet indicate that their function and their frequency response is very similar to how they function in hands [27]. Therefore, the haptic illusions described above should also transfer to feet. However, we are not aware of systems that take advantage of this.

Instead, many systems rely on *grounded kinematic chains*, for example, by providing fully robotic systems that move the entire body and can simulate running or even falling [56]. Other approaches usually focus on specific experiences, for example, Level-Ups can provide the experience of stepping up on to an elevated object [55]. A more subtle approach to grounded systems are shape-changing insoles, which, inspired by *soft-robotics*, use air-filled bladders to render terrain [82, 83]. Yet another approach are *variable friction soles*, where surface features are communicated through changes in perceived friction of the ground [28, 41]. These have also been shown useful in an HCI context, for target acquisition [26].

The above approaches typically involve considerable engineering challenges and cost (cf [45]). A simpler alternative consists of augmenting shoes using *vibrotactile devices*. Here the research focus has primarily been on vibration as a communication device. Examples include communicating language [24] or stock market movements [15]. Other uses include feedback for menu selection [6], navigation instructions [54], and to induce walking rhythms [84]. As these devices do not have any feedback loop for controlling the vibration, they cannot be used for conveying material experiences.

An interesting alternative has been the use of audio for augmenting the footstep experience. Tajadura-Jiménez demonstrated that modifying the sound produced by one's footstep can change the perceived body image, and even influence one's gait [72]. A similar approach is used in a series of studies that use concurrent haptic and acoustic feedback: Visell augmented floors, using vibration generated from audio recordings [79] and Turchet et al. pre-recorded footsteps and presented an algorithm for dynamically playing these back, based on foot-strike intensity [75]. This approach was then used to increase realism in walking over virtual surfaces, though some participants found the experience unpleasant [74]. A related preliminary study by Nordahl et al. [45] explored the same concept using audio-synthesis. They conclude that the auditory channel is more useful than the haptic channel for discriminating between materials. This result is surprising, as research shows that we are not very good at identifying materials through sound [19].

An explanation for the poor performance of the haptic conditions could be that, in the author's own words, *"sensorimotor coupling was inexistent"* [45]. This leads to an experience as if another person was walking for the participant. We expand upon the work by Nordahl and Turchet by providing haptic feedback with full sensorimotor coupling.

### Compliance Illusions

Amongst the first work concerned with designing compliance experiences are mechanical push-buttons with tunable force-pressure profiles by Doerrer [14] and more recent follow-up work by Liao [37, 38]. These prototypes literally change the compliance and haptic properties of pushing a button by a smart combination of mechanical and vibrotactile actuation.

To change the experience of compliance, however, one need not literally change the compliance of a material. Prototypes by Kildal [34] and Lee [35] demonstrate that by providing discrete tactile impulses at fixed changes in pressure exerted, an illusion of compliance can be achieved. Lee also demonstrated that such virtual compliance assists the force control of repetition tasks [3] and lowers physical demand and frustration [22] compared to using a rigid force input device. Similar principles were also deployed at a larger scale on floor surfaces by Visell for displaying compliance and textures [80].

We extend upon the state of the art by demonstrating that this illusion also holds for tactile exploration using feet. We also explore the parameter space and highlight the utility of distinguishing between the salience of the illusion and the accompanying quality.

## Designing Haptic Feedback

Schneider et al. provide an overview of the field of haptic experience design (HaXD) [58], highlighting hurdles and opportunities of the field. Schneider suggests using visual or audio proxies for speeding up design cycles. Schneider and colleagues present various design tools [59] that support sketching [60] and leverage visual and acoustic proxies for designing [61] as well as low-fi vibrotactile representations [62]. An orthogonal approach is exemplified by Pescara et al. who explore the use of evolutionary [50] and genetic algorithms [49] for personalizing vibrotactile patterns, in an iterative process.

Schneider et al. also highlight that problems of HaXD include the difficulty to demonstrate haptic experiences to others. This difficulty, together with the high level of vertical integration (hardware, software, design, psychology) also makes it a challenge for collaborations [58]. Many of the aforementioned design tools, also attempt to address this issue, for example by providing software libraries [63], plugins [59], or authoring tools [81] for creating, organizing, and sharing experiences.

As existing solutions design haptic feedback in a temporal domain, they are incompatible with a system such as *bARefoot*, for which haptic experiences unfold along a dimension of human action. We, therefore, contribute to this existing body of work by providing a design tool for creating and sharing such action-coupled vibrotactile patterns.

## Designing Materials and Shoes

The concept of material experience is also used within design research; Giaccardi and Karana highlight that material experiences are the result of *"mutual interaction between people and objects"* [18]. This is reflected in research methods that emphasize the lived, subjective experience of the design-process [73] as well as approaches that consider the material as a co-performer of the interaction [33].

Such considerations have also been applied to the design of shoes. Nachtigall et al. [43] use a research through design approach to explore how individualized shoes might be created, focusing on the relationship between data and materials. Amorim et al. [5] present a concrete case of using 3D metamaterial structures for creating personalized shoe soles.

Our work shows – empirically – that for designing a material experience, it can be practical to focus on the desired outcome of the *"mutual interaction"* between user and material, rather than the desired material alone.

# BAREFOOT: DESIGN CONSIDERATIONS

Here we describe theoretical considerations that influenced our design choices when implementing *bARefoot*. This section contributes to the following ideas: We suggest explicitly distinguishing between deliberate and perceptive acts. We suggest that a wide range of kinesthetic illusions can be created by adding tactile feedback to perceptive acts. The type of experiences which can be created can be systematically explained by the type of perceptive act that is modified: adding tactile feedback to isotonic acts is experienced as additional friction or counterforce [68], while adding tactile feedback

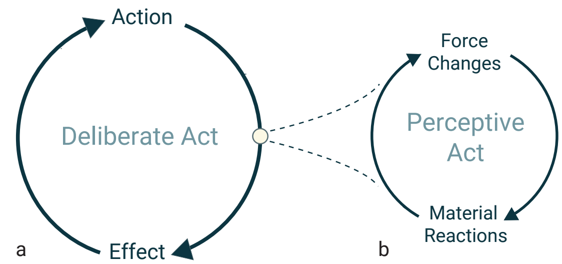


**Figure 1. We distinguish between *deliberate acts* and p*erceptive acts* to guide the conceptualization and design of sensorimotor coupling.**

to isometric tasks is experienced as additional compliance or movement [23, 34]. Finally, we suggest that focusing on generating experiences and parameterizing is an important tool towards the sharing of tactile experiences and an important step towards general-purpose tactile displays.

## Designing for Perceptive Acts

Sensorimotor coupling is often mentioned as an important concept in HCI, especially with regard to embodied interaction [76]. We suggest that explicitly distinguishing between *deliberate acts* and *perceptive acts* helps in conceptualizing and actualizing design for sensorimotor coupling. We suggest using the temporal dimension of interaction as a distinguishing factor. Traditionally, interaction design focuses on deliberate acts and their outcomes, which usually occur in the range of hundreds of milliseconds [44]. For example, a user might flip a lightswitch (*Action*) and perceive that the room is now well lit (*Effect*). We refer to this as a *deliberate act* (Figure 1a).

Embedded within this deliberate act is a loop of perceptive acts: While pushing against the switch, the user perceives its friction, the force required for it to flip, and other properties such as the texture of its surface. These material properties are perceived through interaction between changes in applied force, and a corresponding reaction of the switch and deformation of the fingertips (Figure 1b). These tightly coupled sensorimotor loops continuously occur when interacting with materials. Work such as the dynamic buttons by Liao et al. [38] caters to these sensorimotor loops, while prototypes such as PseudoBend [23] or ReFlex [69] leverage such sensorimotor coupling for creating haptic illusions. When designing for such perceptive acts, the literature suggests that tight temporal coupling is essential [86]. Participants have reported experiencing the effect of latency as low as $\sim 25$ ms [68] and studies on musicians suggest that even $\sim 10$ ms delay might interfere with the perceptive act [39].

Deliberate acts and perceptive acts complement each other. Walking on a gravel path in the woods, one might deliberately step off the path on to mossy grass. One might then perform a series of perceptive acts, as the force of the shoe and the counterforce of the moss provide a rich experience of the complex surface. Similarly, we suggest that interactive technology might consider each interaction loop separately. If the above example happened in a virtual world, it would be sufficient to update which material to render (gravel path or mossy grass) at less than 60Hz (cf. [31]), while the material interactions (probing of the mossy grass) would require an update rate of well over 100Hz (cf. [39]).

### Considering the Breadth of Motor Acts

Often vibrotactile rendering systems limit their design to either isotonic (e.g., [12, 53, 68]) or isometric acts (e.g., [23, 34, 35]). We wish to highlight that these two design approaches both share augmenting perceptive acts with tactile cues as their underlying mechanism. The resulting experiences share a certain symmetry with the perceptive acts: Systems, where the user can freely move, are experienced as restricting movement if tactile cues are added, for example, users might feel friction, where there is none [68]. Systems where the user's range of motion is constrained provide an experience of movement if tactile cues are added, for example users might feel compliance, even though the material is rigid [34].

In the context of designing for foot-based material experiences, this provides us with a range of options to consider. Human gait consists of two components: an isotonic swing phase, where the foot is lifted off the ground, which might be augmented with friction or resistance [68] and an isometric stance phase, where the foot is in contact with the ground, which might be augmented with additional experiences of motion [23, 34] (see Figure 2). Additionally, when lifting and placing the foot, these types of motion might overlap, and when stepping on many materials, elastic interaction occurs which includes both isometric and isotonic components (cf. [69, 91]).

We suggest that general purpose systems for creating virtual material experiences should be able to measure and respond to both isotonic and isometric motion, providing tactile impulses at fixed measure in either dimension (See Figure 2). In this paper, we focus on the compliance illusion. The reason for doing so is that it is well understood in other domains [3, 34, 35], and therefore an ideal first step in exploring this space.

### Providing Knowledge of Performance

In the context of motor learning, a distinction is commonly made between inherent and augmented feedback. Inherent feedback is intrinsic to the activity which is performed, while augmented feedback is information that is provided externally. Inherent feedback is naturally concurrent to the action, while augmented feedback can be either concurrent or be provided terminally after the action is completed [57].

Feedback can provide knowledge of the result (KR) or knowledge of performance (KP) of an action. Knowledge of results describes the outcome (you hit the target), while knowledge of performance instead describes how the task was performed (your knees were bent) [57].

Typically, augmented feedback is provided verbally, terminally, and provides information about results [57]. In contrast, the methods we suggest here are designed to blend in with the intrinsic kinaesthetic feedback and provide concurrent knowledge of performance.

### Parameterizing Haptic Experiences

It is relatively trivial to explain what combination of colors makes something appear green. Making similar statements about material experiences is difficult. While work which has prerecorded material properties [53, 74] has been able to reproduce these with a high degree of realism, these explorations do

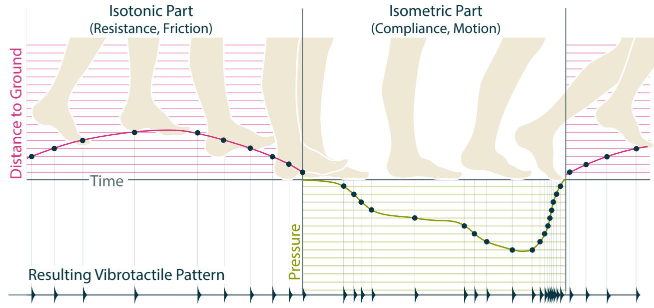


**Figure 2. Walking can be separated in a swing phase (isotonic) and a stance phase (isometric). *bARefoot* measures human activity in the swing phase using an inertial motion sensor (IMU), and in the stance phase using a pressure-sensitive sole. Using this information, it provides tactile impulses – grains – at fixed intervals relative to user actions.**

not provide any information on why something feels the way it does. Another common approach does not focus on realism but instead explores how tactile parameters map to haptic experiences [29, 70]. This second approach has the potential not only to create complex material experiences, but also to help us understand which parameters cause this experience, similar to knowing which combination of colors creates green.

We suggest focusing on the parameterized approach for several reasons. Not only does it have the potential to facilitate a better understanding of haptic perception, it also facilitates communicating material experiences. The ability to describe a material experience with as few parameters as possible might support simple standardized encoding for reproducing and sharing them. Understanding how the parameters of this encoding affect the experience would also ease the augmentation of visual virtual worlds with material experiences, as a visual texture might automatically generate the corresponding parameters.

## IMPLEMENTATION

We present a haptic shoe – *bARefoot* – with methods for generating virtual materials. We demonstrate that *bARefoot* can complement existing VR and AR technologies by presenting an example of *bARefoot* integrated into a Unity application. To facilitate the design of virtual materials, we also provide a flexible design tool called *vibrAteRial*.

### bARefoot

Based on our design considerations, we decided that all aspects of generating textures should happen in the firmware

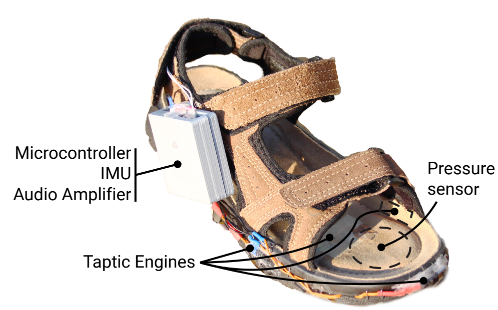


**Figure 3. *bARefoot* consists of a sandal augmented with Taptic Engines for providing tactile cues, and inertial motion (IMU) and pressure sensors to sense the user's actions.**

of the haptic shoe itself. By having the sensing and virtual material generating functions as part of a high-frequency embedded system, latency can be minimized and sampling rates maximized, to optimally respond to high-frequency perceptive acts. Each *bARefoot*, both left and right, is fully operational on its own. It can provide a virtual material experience without requiring communication with any other device. Here we describe its electrical implementation, hardware, and sensor processing setup[1].

### *Hardware*

In selecting sensors and micro-controllers, we were primarily interested in ensuring fast update rates. The electronics of *bARefoot* were controlled by an ESP-32. We chose to use the ESP-32 as it can operate at up to 240 mHz and because it supports wireless communication. For easier development, we used the ESP-32 Dev Kit C V4 by AZ-Delivery.

We used two high-resolution sensors: a pressure sensor for measuring the force applied to the ground during the stance phase of walking or when probing the ground, and an inertial measurement unit (IMU) for measuring foot-motion during the swing phase. The pressure sensor was custom made of Eeonyx non-woven piezo-resistive fabric (cf. [25]), so it could be easily integrated into the sole of the shoe. The update rate is limited to the speed of the ADC conversion which exceeds 25k conversions per second. As IMU we chose the LIS3MDL by Pololu which can provide update rates up to 1 kHz. We measured the time from receiving a signal at the ADC to providing a corresponding output on the DAC to be <0.16ms.

The analog output of the ESP-32 was connected to a class D amplifier that received external power from phone-charging power-banks, carried in the user's pant-pockets. The amplifier was used for driving four Taptic Engines, connected in parallel. Please refer to Figure 3 for a photograph of *bARefoot* and Figure 4 for details of how components connect.

We designed the *bARefoot* prototype using a sandal to easily adapt to a wide range of foot sizes and make modifications of the shoe, such as integrating components in the sole, easier (Figure 3). It is to be noted, however, the concept of *bARefoot* does not depend on a specific form factor.

### *Sensor Processing*

As any jitter in the input signal would negatively input sensorimotor coupling, we paid special attention to stabilizing the signal measured from the pressure sensor. We first used a running median of seven values to remove outliers. To smoothen the data, we then applied a low-pass filter (cf. [2]).

To ensure that idiosyncrasies of the non-linear response of the piezo-resistive material would not influence the material experience, we linearized the sensor output: We first measured the sensor response to known forces, calculated the function which best fits the resulting curve, and then multiplied the measured values by the inverse of that function.

To optimize IMU readings, each accelerometer and IMU were calibrated in a resting state. Hard and soft iron calibration was conducted on the magnetometer, once mounted to the

[1]all code is available at `vibraterial.github.io`

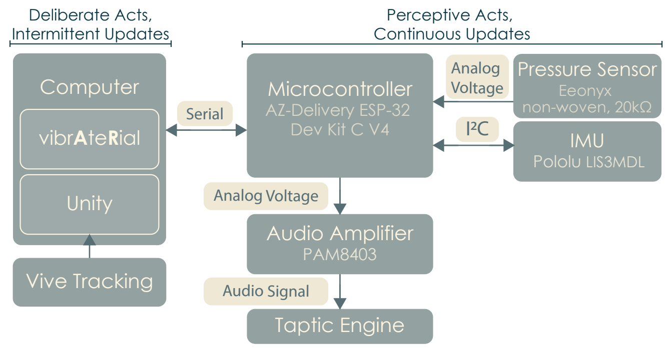


**Figure 4. General architecture of *bARefoot*. Components on the left are only required to instruct *bARefoot* to switch between virtual materials. Components on the right are required for rendering virtual materials.**

shoe, using the Teensy Motion Sensor Calibration tool. The readings were fused using the NXP sensor-fusion algorithm as implemented in the NXPMotionSense Arduino library. The resulting signal can be used for sensations previously described as *rotation* condition by Strohmeier et al. [68, 67]. As these sensations are less well understood than the compliance illusion, we chose to not focus on these for the initial presentation of *bARefoot* but intend to revisit these in future work.

## Unity Integration

While *bARefoot* has access to all information for rendering a virtual material experience, it does not have the information required for switching between corresponding virtual materials, as the user steps from virtual grass to virtual stone. Such information needs to be provided by an application which tracks deliberate acts.

For VR applications, this information is provided by a custom Unity application. HTC Vive position trackers are mounted on *bARefoot*. Knowing the position of each foot in the virtual world, one can identify which virtual material the shoe should interact with and send the corresponding settings to *bARefoot*. Consequently, when the user moves from one virtual surface to another in VR, the corresponding virtual texture will also switch. It should be noted that, as the virtual material is generated by each *bARefoot* individually, potential latency between *bARefoot* and Unity does not impact the performance of the shoe (Figure 5). Using a Serial connect to *bARefoot*, we estimate the system latency to range between 10.7 ms and 21.8 ms.

**Figure 5. *bARefoot* prototypes augmented with HTC Vive sensors to track the positions of the user's feet (left). First-person view of the VR application within which the user can experience walking on various virtual materials.**

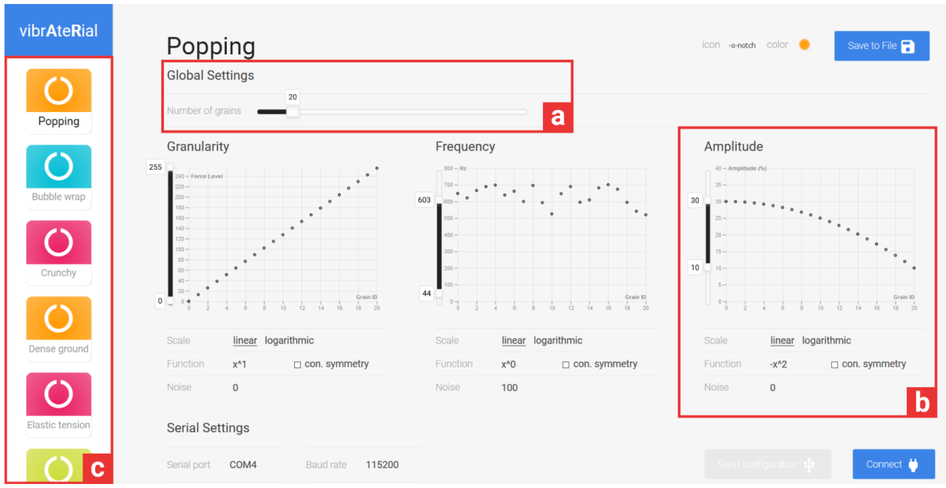


**Figure 6. Overview of the *vibrAteRial* design tool. *vibrAteRial* enables creating vibrotactile patterns as a function of the user's actions by direct manipulation of their parameters. The user can simply set the number of grains (a) and manipulate their distribution, frequency, and amplitude (b). *vibrAteRial* enables switching between a list of patterns (c), as well as saving and sharing patterns with others.**

This overall architecture matches the design considerations of separating deliberate acts (which are handled by Unity) from perceptive acts (which are handled in high frequency by *bARefoot*). This allows evaluating one aspect of the system without worrying about the other. It is also beneficial for wireless communication as we need not worry about jitter. Finally, it scales well to an AR context – even if position information is not available in high resolution, *bARefoot* can still provide high-resolution material experiences[2].

### Generating Virtual Materials

To simulate virtual material, discrete pressure values are mapped to bursts – or grains – of vibration. For example, if we define 128 grains over the entire range of available pressure, as the user slowly increases the pressure, individual impulses occur at discrete pressure levels. When hitting the halfway mark, the user will have experienced 64 bursts. When releasing the pressure again, the user re-encounters the grains at the same pressure levels. Different virtual materials can be provided by varying the number of grains, or the properties of the individual grains.

Each grain is created as a sine-wave burst. *bARefoot* supports manipulating the frequency, duration, and amplitude of individual grains. For the purpose of making each grain as short as possible, we fixed their duration to their wavelength. This effectively provides us with two parameters that manipulate grains: *frequency* and *amplitude*. We report frequency in Hz and amplitude in the percentage of the maximum output of the amplifier.

In addition to manipulating these parameters, one can adjust the *granularity* of a virtual material, by either modifying the total number of grains or changing the way grains relate to the user's action: Instead of being linearly distributed over the entire range of pressure, for example, one can skew their placement to one end, or place them randomly. Similarly, the frequency and amplitude of individual grains can also be adjusted.

[2] 4 ms input delay of Vive controller [1], up to 11.11 ms delay from the game engine (updated at 90 Hz), 6.5 ms measured delay for sending a texture via Serial, < 0.16 ms measured until the DAC is pulled high.

### Designing Experiences

Design tools for creating vibrotactile patterns are an active research area [49, 60], with strong examples of intuitive haptic editors, such as Macaron [61]. All existing editors provide tools for manipulating haptic parameters *over time*. These are not applicable to *bARefoot* and related sensorimotor coupled haptic feedback systems, as their relevant dimension is not time, but *human action*.

To design vibrotactile patterns for *bARefoot*, we therefore designed a custom tool – *vibrAteRial* (Figure 6). It is designed for freely exploring the parameters supported by *bARefoot*. *vibrAteRial* supports simple and rapid creation of custom vibrotactile patterns. We provide multi-modal representations of these patterns: they are immediately visually represented in the tool, they can be sonified, and they can be sent to *bARefoot* for tactile exploration.

#### *Creating Experiences*

Typically, a user might first select the overall number of grains using a slider (Figure 6a). The distribution of grains and their corresponding frequency and amplitude can then be individually manipulated. Initially one can input a function the parameter should follow, which is then automatically scaled to the selected value range (Figure 6b). This function can be also reflected along the diagonal axis, for creating the inverse effect. One can then add randomness with the noise tool. Once the general parameters of the experience are satisfactory, individual grains can be directly manipulated, by moving them to their desired location in the corresponding graph.

#### *Exploring and Sharing Experiences*

*vibrAteRial* uses a standardized encoding of the vibrotactile patterns supported by *bARefoot*. It allows saving multiple patterns and quickly switching between them, for quick comparisons (Figure 6c). Vibrotactile patterns can also be exported and saved as a JSON file, for remote collaboration between researchers[3]. Using *vibrAteRial* one can load a pattern designed by a colleague, visually inspect it, listen to a sonification of it, or upload it to a *bARefoot* for tactile exploration.

[3] This was put to a practical test in writing this paper, as none of the authors were co-located due to the ongoing COVID-19 situation.

*Implementation.*
*vibrAteRial* consists of a Node.js server communicating between an HTML interface (full screenshot can be seen in Figure 6) and *bARefoot* through serial. However, the tool does not require a connection with *bARefoot* to work and can be used as a standalone, for 'offline' design of haptic experiences, using the visual and auditory feedback.

## EXPLORATIONS OF THE PARAMETER SPACE

These explorations were conducted by four of the authors. Using experts as participants has various advantages: Reflecting on haptic experiences is difficult as we do not share a strong vocabulary describing these (cf. [46]). Psychophysics experiments also require training, focus, and concentration. The quality of the resulting data depends on a large part on the ability of the participant to reflect on their experience (cf. [51]). Using experts who are familiar with psychophysical scaling tasks, made it easier to conduct initial tests successfully.

The authors performed the experiments in their homes and were unable to communicate during the tasks. We do not believe that any systematic bias was inserted by desirability effects, as none of the authors is particularly invested in any specific parameter or its level. Results were only shared once all authors had completed the experiment. The results are primarily intended as a proof of concept, to demonstrate that this type of experiment can be conducted with *bARefoot*. While we believe that the trends we found will generalize, we caution on any interpretations beyond, and explicitly refrain from hypothesis testing.

### Exploration 1 - Linear and Constant Parameters

The purpose of exploration 1 is to better understand how to optimize the parameters for generating an experience of compliance. The compliance illusion itself is well established in the literature [34, 35]. So far, however, there is little guidance on how to specifically design the illusion to optimize its effect. Specifically, we were interested in understanding the effects of varying the number of pulses, and whether these were influenced by frequency.

*Independent Variables*
In **task 1**, the *frequency* was fixed at 220 Hz (corresponding to the musical tone $A_3$) and users compared 10 levels of *granularity* (5, 8, 13, 20, 29, 40, 53, 68, 85, and 104 grains).

In **task 2**, we explored if granularity interacts with frequency. We combined four levels of frequency (110 Hz– $A_2$, 175 Hz– $F_3$, 277 Hz– C#$_4$, and 440 Hz– $A_4$) and five levels of granularity (5, 13, 29, 53, and 85 grains) in a fully factorial design.

Each grain used a pulse-length corresponding to its wavelength. To accommodate the effect of pacinian frequency response (cf [78]), and potential signal attenuation by the material of the shoe, each participant individually calibrated each frequency, so that they were all experienced as equally strong. We report the means and standard deviations of these calibrations: 110 Hz **3**% *(1.41)* | 175 Hz **3.5**% *(1.73)* | 277 Hz **7.5**% *(2.38)* | 440 Hz **29.35**% *(12.5)*.

We use a within-subject design. Each task consisted of blocks that include all combinations of the independent variables. We randomize these combinations within each block. Each task starts with a training block and is followed by 3 blocks in task 1 and 4 blocks in task 2. It took approximately an hour to complete each task.

*Dependent Variables*
Following a standard magnitude estimation procedure [17], we collected three estimates for each stimulus – the **Salience** of the illusion (*how clearly can compliance be felt?*), and two characteristics of the quality of compliance: **Continuity** (*is the experience holistic, or is it separated in discrete sub-experiences?*) and **Depth** (*how far does the foot 'sink'*). Estimates were input using three dynamic sliders (cf. [40]).

*Data Processing & Visualization*
As the data set of each participant has its unique scale, all sets need to be reduced to a common measure [46, 70]. This is done by standardizing each data set individually (cf. [65]), according to the average variability of all estimates. We use the resulting 95% confidence interval (CI) as a measure of this variability. The resulting data has an average of zero, and an average 95% CI of $\pm$ 1 (cf. [67]).

For **task 1**, for each estimate, we plotted the average values for each participant and their corresponding CI's (Figure 7). For **task 2**, we created heat-maps for each estimate (Figure 8). These show the grand mean and the corresponding 95% CI for each combination of *frequency* and *granularity*. The color scale is shared over all three heat-maps and highlights estimates of -3 or lower in red and estimates of 3 or higher in green. Other colors vary linearly between these.

### Results

By collecting estimates of salience separately from estimates of quality, we can consider the questions of how well the illusion of compliance works separately from descriptions of what the compliant sensation felt like. Interestingly we found that, in both tasks, the overall salience and the experience of depth or continuity only poorly correlate.

**Task 1:** Looking at *salience* (Figure 7, left), we found that stimuli spanning between 13 and 53 grains were rated highest. Stimuli with more grains were generally rated lowest. A possible explanation for this is that because the occurrence of grains was so frequent, a fast motion would truncate grains, injecting higher frequency artifacts into the experience, which were only indirectly coupled to pressure and therefore detracted from the experience. There was large variability in the rating of stimuli with very few grains. This can be explained by the observation that the illusion with few grains did work well (similarly to the single-grain depth illusions used in some contemporary devices), but that it was, compared to the satisfying experience of the higher-rated stimuli, relatively disappointing.

We found that both the experience of *depth* (Figure 7, middle) and *continuity* (Figure 7, right) increased with the number of grains, but only to about 53 grains. Above that, adding grains did not appear to further augment the experience. In fact, for continuity, some felt that more grains lead to discontinuity. The discrepancy between our results for continuity can be explained by how we engaged with the device – by

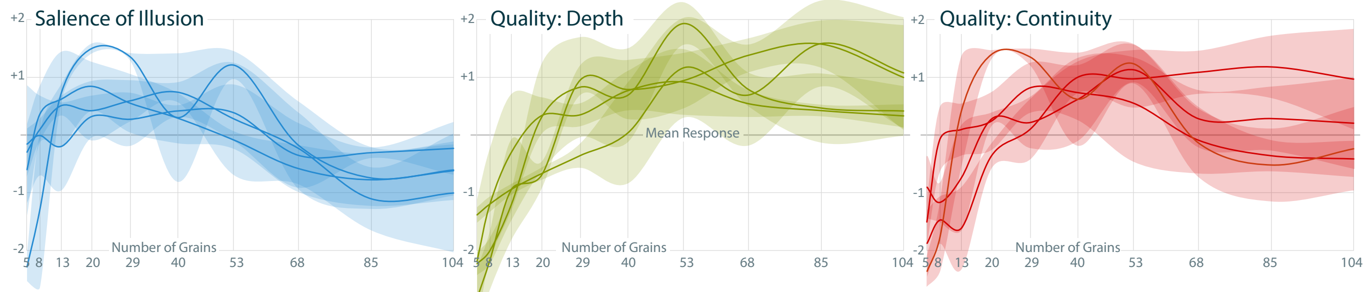


**Figure 7. Standardized results of the magnitude estimations from task 1 (Exploration 1). Each line represents the standardized average of a participant for each grain number, and areas of the same color their 95% CIs**

moving deliberately slowly, one can avoid the problems of high granularity explained before.

**Task 2:** We now discuss the influence of frequency of the individual grains. The heat-maps shown in Figure 9 suggests that there are interaction effects between the number of grains and the frequency. The heat-map for *salience* shows the least variability in average ratings, however, the combinations with the highest ratings typically had either 29 grains or 277 Hz. Combining low frequency with high granularity had a negative impact on the illusion.

The results for *depth* (Figure 9, bottom left) are in line with our suspicion that a high number of grains might be rated negatively due to the truncating of grains. We see that for 85 grains, the rating radically drops for the 110 Hz condition, which is what we would expect. Looking at *continuity* (Figure 9, bottom right), it also appears that higher frequencies make the individual pulses more prominent. As the number of grains increases, grains with higher frequencies appear to harmonize better, resulting in more continuous experiences.

It should be highlighted that these estimates only describe the experience relative to one another and that it is not possible to draw absolute conclusions from this type of magnitude estimation data [17]. In other words, looking at the *salience* measures, the low ratings of both low and high number of grains does not mean that these settings worked badly, it merely means that the others worked better. Conversely, it also means that high ratings solely highlight better illusions than the others.

Salience of Illusion

| | 5 Grains | 13 Grains | 29 Grains | 53 Grains | 85 Grains |
|---|---|---|---|---|---|
| 110 Hz | -1.70 ± 1.17 | 0.01 ± 1.16 | 1.38 ± 0.97 | -0.11 ± 0.82 | -2.20 ± 1.42 |
| 175 Hz | -1.18 ± 1.18 | -0.16 ± 1.24 | 1.45 ± 0.52 | 0.25 ± 1.37 | -1.25 ± 1.27 |
| 277 Hz | -1.32 ± 1.06 | 1.43 ± 0.69 | 1.05 ± 0.74 | 1.15 ± 0.63 | 0.26 ± 0.88 |
| 440 Hz | -1.45 ± 1.12 | 1.04 ± 0.92 | 1.12 ± 0.75 | 0.34 ± 0.87 | -0.10 ± 0.93 |

Quality: Depth

| 5 Grains | 13 Grains | 29 Grains | 53 Grains | 85 Grains |
|---|---|---|---|---|
| -3.60 ± 0.83 | -1.44 ± 1.35 | -0.22 ± 1.10 | 1.01 ± 0.75 | 0.00 ± 1.54 |
| -3.12 ± 0.94 | -1.13 ± 1.44 | 0.38 ± 1.32 | 2.01 ± 0.73 | 2.46 ± 1.29 |
| -3.41 ± 0.84 | -1.44 ± 1.26 | 0.74 ± 0.84 | 3.45 ± 1.51 | 3.71 ± 1.65 |
| -3.92 ± 0.55 | -0.96 ± 0.93 | 0.59 ± 0.89 | 1.28 ± 1.17 | 3.62 ± 1.79 |

Quality: Continuity

| | 5 Grains | 13 Grains | 29 Grains | 53 Grains | 85 Grains |
|---|---|---|---|---|---|
| 110 Hz | -1.60 ± 1.02 | 1.15 ± 1.27 | 1.65 ± 0.80 | 1.20 ± 0.87 | -0.51 ± 1.38 |
| 175 Hz | -2.47 ± 0.91 | 0.36 ± 1.01 | 1.75 ± 0.86 | 1.37 ± 1.21 | 0.10 ± 1.54 |
| 277 Hz | -3.01 ± 0.85 | -0.08 ± 0.95 | 1.21 ± 0.78 | 1.64 ± 1.05 | 1.82 ± 0.92 |
| 440 Hz | -3.08 ± 0.81 | -1.03 ± 0.57 | 0.50 ± 1.03 | 1.53 ± 0.74 | 0.89 ± 0.89 |

**Figure 8. Heat-maps of the results of each estimate (salience, continuity, depth) from task 2 (Exploration 1). Large numbers denote the grand mean and smaller numbers their 95% CI for each combination of frequency and granularity.**

### Exploration 2 - Non-constant parameters

Next, we explore the effects of non-constant parameters. With non-constant parameters, we refer to parameters which change from grain to grain, either randomly (cf. [34]), or as a function of applied pressure. While the previous exploration was based on a previously established illusion, the opportunities of non-constant parameters have so far barely been explored. As an initial sampling of the parameter-space, we explore concave and convex granularity, random and constant frequency, as well as rising and falling amplitude.

#### *Comparisons*

We made three comparisons to better understand the *shape of curve* (convex/downward or concave/upward), *randomness*, and *direction* (rising or falling) of varying parameters. We presented these comparisons to participants in both orders (A:B and B:A) and repeated each order 3 times, for a total of 18 comparisons. The comparisons were presented in random order, blocked by repetition. For each comparison participants were asked to name 3 words which best described the difference between two virtual materials and indicate for which of the two stimuli the description applied more. Details of the virtual materials will be described per comparison. We used 25 linearly distributed grains, 200 Hz, and 5% amplitude if not otherwise specified. Screenshots of exact settings are available in the appendix.

We removed duplicate and opposite terms and then grouped the reported words by *normative judgments* (Blue), *materials and textures* (Green), and *reaction of material* (Red) – See Figure 9.

*Convex*  *vs Concave*  *Granularity:*
For comparing curvature, we changed the slope of how grains are distributed. In the concave condition, the grains follow a function of $x^2$. The convex condition mirrors this curve along its linear axis. The result is that for the convex condition the grains arise closer to each other early on in the movement, which most likely explains that it was experienced to be more *reactive* (*sensitive*, *closer*) than the concave condition. In the concave condition, the initial grains are rather sparse and only become more frequent with high pressure. This was experienced as *dull* or *muted* (see Figure 9, top).

CONCAVE GRANULARITY ⟷ CONVEX GRANULARITY

- Concave granularity:
  - ▶ rigid, rocky
  - ▶ dull, muted, subtle
- Convex granularity:
  - ▶ artificial
  - ▶ compliant, dry, elastic, fragile, sandy, soft, strong, thick, viscous
  - ▶ bouncy, closer, crunchy, loud, malleable, reactive, sensitive, sticky

RANDOM FREQUENCY ⟷ CONSTANT FREQUENCY

- Random frequency:
  - ▶ complex, uncomfortable
  - ▶ granular, pebbles, rigid, rocky, rough
  - ▶ crunchy, dull, sticky, stuttering
- Constant frequency:
  - ▶ artificial, familiar, nice
  - ▶ compliant, deep, soft, woody
  - ▶ bouncy, consistent, continuous, smooth, springy

RISING AMPLITUDE ⟷ FALLING AMPLITUDE

- Rising amplitude:
  - ▶ rich
  - ▶ elastic, rigid, sandy, soft, strong
  - ▶ dull
- Falling amplitude:
  - ▶ cheap
  - ▶ fragile, rocky, rough
  - ▶ alive, immediate, moving, long, loud, springy, sticky, reactive

**Figure 9. Terms used to describe each virtual material. We categorized these according to *normative judgments* (blue), *materials, and textures* (green), or the *reaction of the material* (red).**

*Random vs Constant Frequency:*
Here we were interested to compare constant and random parameters. We focused on frequency by comparing a constant frequency of 200Hz to random frequencies ranging between 0 Hz and 590 Hz. The effect was a somewhat unpredictable experience for the random condition, which was slightly *uncomfortable*, compared to the smooth predictable behavior of the constant frequency. However, the random condition also evoked more natural experiences, while the fixed condition was described as a comparatively *artificial* experience with *springy* and *bouncy* properties (see Figure 9, middle).

*Rising vs Falling Amplitude:*
Finally, we compared the effect of increasing to decreasing a parameter coupled to user action. We chose to focus on the amplitude and presented a condition where it rises to a comfortable level compared to a condition where the amplitude starts at a comfortable level and then falls. We found that the falling amplitude felt more *reactive* (*alive*, *immediate*) than the rising amplitude, most likely due to the more prominent grains at the start of the movement. However, the rising amplitude was also associated with a *richer* experience, while the material experience of falling amplitude was described as *cheap* (see Figure 9, bottom).

This second exploration highlights that not only the current parameters shape the material experience. The dynamics of how parameters are changed as a function of user input, have a substantially influence on the experience as well.

### Exploration 3 - Design of Virtual Materials
To get a better impression of the materials which might be created and to explore if our editing tool provided us with the ability to design materials to our satisfaction, we spent time testing and sharing materials between the authors. Our goal was to design novel material experiences to demonstrate the breadth of experiences *bARefoot* can create. Here we provide a sampling of materials.

*Foam*
150 Grains: , Freq: 0 250 ($x^2$), Amp: 7 0
This material experience was described by its designer as *"[moving] through the foam with your hand"* when taking a bath and *"every little bubble [is] bursting"*. This feeling of very light grains was likely produced by the combination of a high number of grains coupled with low amplitude levels. This follows our findings from exploration 2 that a falling amplitude evokes *fragile* materials (Figure 9).

*Air bubble*
12 Grains: ($x^{0.3}$), Freq: 600 , Amp: 10 20
This material experience was described by its designer as *"a thin air bubble that one could easily pop"*. The granularity is likely the main factor in this feeling as grains occur more frequently as the pressure increases. The rising amplitude accentuates this feeling of *"popping"* when reaching the maximum pressure level. The low number of grains might explain why this material felt *"thin"*.

*Crunchy*
16 Grains: ($x \pm 6$), Freq: 740 147 ($x^2$), Amp: 18 5 ($x \pm 5$) The primary asset of this material is to feel *"natural in the sense that I really feel the material changing below my foot"*. When pressing against the ground, this experience is comparable to *"grains compressing against each other like [stepping on] snow"*. This feeling of *naturalness* is likely produced by the noise added to the granularity and amplitude, as we observed with the random frequency (see Figure 9).

*UI mechanism*
30 Grains , Freq: 390 710 ($x^3$), Amp: 5 20 ($x^3 \pm 4$) This material is peculiar as its designer reported *"an interesting sense of agency"*. The designer felt in control of the material like controlling the foot pedals of a car. This material experience felt *artificial* and might be used to leverage haptic UI mechanisms. This feeling of artificiality was likely produced by the mix of high frequencies with random amplitude levels.

## REFLECTIONS ON USE CASES
### Foot-Based 3D Button
While foot-based user interfaces have been explored extensively in HCI [77], they often rely on visual feedback [7] or vibrotactile notifications [6], providing knowledge of the outcome of an interaction. Using *bARefoot* one might also provide tactile guidance or feedback of performance, as the interaction unfolds (cf. [57]), For example, we propose adding an experience of compliance to pressure based interaction:

When interacting with a virtual 3D button on the ground, the pressure sensitivity of the shoe can be used to infer how far the button is pressed, and the virtual compliance sensation can provide corresponding feedback to the user, augmenting the kinaesthetic perception of their action (Figure 10).

The results of our explorations suggest one could adapt the *depth* of the virtual material to generate various categories

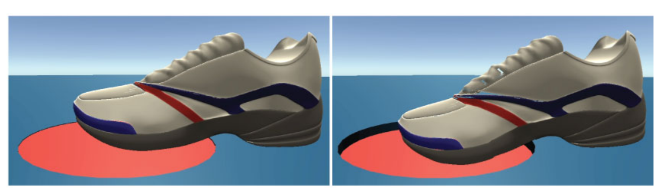

**Figure 10. Foot-based 3D button. *bARefoot* creates an experience of compliance at the position of the button to create the illusion of the foot pushing the button down.**

of buttons. Furthermore, the input mapping could change to span from a two-state button to a value picker to select multiple entries, following similar techniques designed for hand interactions [11, 52]. Using bursts in the amplitude of given grains would serve as landmarks to facilitate selecting entries, as it is often used in with dials in cars. Related research suggests that such virtual materials might improve control in repeating tasks [22].

### *Improving Immersion in Virtual Environments*
Immersion in virtual environments often relies on visual and auditory cues which might be extended with tactile information. This has led to a breadth of research prototypes for providing haptic feedback in VR, usually in the form of handheld controllers [64, 85, 90]. Such tactile interactions, however, are also important for foot-based interaction:

In Figure 11, the user walks through a pier made of old wood planks in a virtual environment. Visually, the user cannot clearly identify if the plank will support their weight, but they can haptically probe each plank to evaluate its strength before stepping on it. barefoot also enables augmenting both the swing and stance phases of walking inside virtual environments. For instance, when the user walks on grass, one can design a material experience comparable to stepping on soft earth for the stance phase and design a material experience comparable to hitting grass leaves with the foot for the swing phase (see Figure 12).

### *Augmenting Running*
HCI research has started to address both the efficacy of running exercise [42] as well as the immersion and enjoyment of the process [4]. A review by Jensen and Mueller [30] highlights that there is a lack of technologies that provide complex technique-related feedback to the runner in an assertive manner. This might be addressed with *bARefoot* by providing concurrent feedback on running performance (cf. [57]). Additionally, changing materials properties of the ground might be used as a storytelling tool [88], or enhance otherwise mundane running experiences, such as running on a treadmill.

### *Subtle notifications for Embodied Experiences*
One can also use the material experiences generated by *bARefoot* as means to convey subtle, non-disruptive information. This approach leverages the fact that tactile information processed by the feet is rarely the focus of one's attention, but strong stimuli can call for attention (e.g., stepping on something soft while walking on concrete). One could map information such as the remaining distance to walk to a given

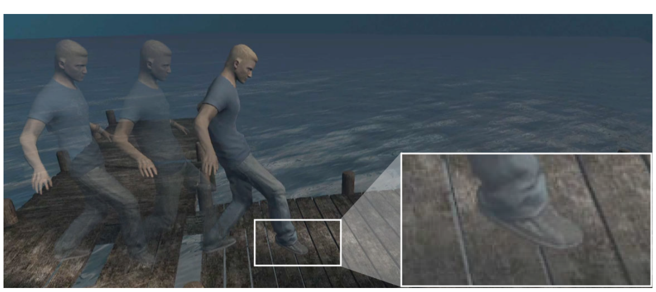

**Figure 11. *bARefoot* enables probing of virtual grounds. To avoid falling the user probes the strength of each plank before stepping on it.**

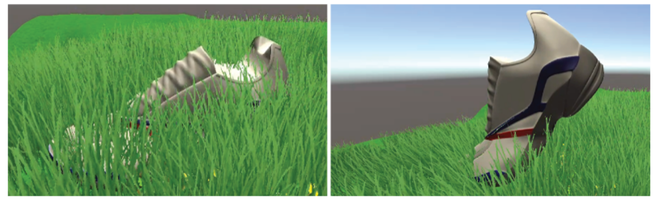

**Figure 12. *bARefoot* enhances the walking experience in virtual environments. In the stance phase, the user can feel the compliance of the earth (left). In the swing phase, light vibrations are emitted to simulate the friction of the grass on the shoe (right).**

destination, or subtle navigation cues [16] to the material experience of walking.

One might also map environmental information that the human body usually cannot perceive to material experiences. For example, *bARefoot* might convey ambient pollution levels [48] or WiFi strength [20] as friction in the air, by providing grains coupled to isotonic movement of the shoe (cf. [68]).

## FUTURE WORK
Going forward, an important extension of this work will be *Non-Symmetrical Granularity:* i.e., one might provide different experiences for pressing and releasing pressure. An obvious parallel from the natural environment is crushing a fragile object by stepping on it. We would also welcome further exploration of the *Frequency Range*. Based on our initial results, it would be especially interesting to explore the high continuity experienced with low frequencies and the interaction between frequency and granularity further. In this context, it would be prudent to also explore *psychophysical scaling* methods [32] and consider interactions between pressure and perception of tactile cues [47]. Also, while qualitative user experience has been the focus of previous work [68], similar qualitative inquiry is also needed for optimizing realism. *Realism* could, for example, be further strengthened by providing multimodal feedback. Combinations of tactile with acoustic [75] or visual [13] feedback might greatly enhance realism when designing real-world applications using *bARefoot*. Finally, we would like to see the approach presented in this paper used with *other technologies* such as on-body feedback devices [21], electrotactile epidermal skins [87], or vibrotactile implants [71].

## CONCLUSION
We presented *bARefoot*, a novel prototype shoe for providing motion coupled vibration. This enables creating virtual materials. We highlight the potential of motion coupled vibration to create sensations similar to compliance, elasticity, and other material experiences. We also presented *vibrAteRial*, a design tool for exploring novel material experiences and creating virtual materials. Our initial explorations indicate that salience and qualia of the compliance illusion can be separated and that salience, depth and continuity of the illusion are influenced by interaction effects between granularity and frequency. We show that the dynamics of a parameter as a function of user input also shape the material experience. Finally we present example materials and use cases to demonstrate how *bARefoot* can improve interactions.

## ACKNOWLEDGEMENTS

This project received funding from the European Research Council (ERC StG Interactive Skin 714797). Many ideas presented here were initially explored during Paul's time at the University of Copenhagen and his stay with the MIT Media Lab's Responsive Environments group. Paul is grateful for the support he received from the HCC Section and thanks Resenv for their hospitality.


## REFERENCES


[1] 2016. Doc-Ok.org. (2016). http://doc-ok.org/?p=1478 Accessed: 2020-05-05.

[2] 2020. Arduino code techniques. (2020). https://wiki.ardumower.de/index.php?title=Arduino_code_techniques Accessed: 2020-05-05.

[3] Teemu Ahmaniemi. 2013. Effect of Dynamic Vibrotactile Feedback on the Control of Isometric Finger Force. *EEE Trans. Haptics* 6, 3 (July 2013), 376–380. http://dx.doi.org/10.1109/TOH.2012.72

[4] Albara Alohali, Kai Kunze, and Robert Earle. 2016. Run with Me: Designing Storytelling Tools for Runners. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct (UbiComp '16)*. Association for Computing Machinery, New York, NY, USA, 5–8. http://dx.doi.org/10.1145/2968219.2971452

[5] Davide Jose Nogueira Amorim, Troy Nachtigall, and Miguel Bruns Alonso. 2019. Exploring Mechanical Meta-Material Structures through Personalised Shoe Sole Design. In *Proceedings of the ACM Symposium on Computational Fabrication (SCF '19)*. Association for Computing Machinery, New York, NY, USA, Article 2, 8 pages. http://dx.doi.org/10.1145/3328939.3329001

[6] J. Anlauff, T. Kim, and J. R. Cooperstock. 2018. Feel-a-bump: Haptic feedback for foot-based angular menu selection. In *2018 IEEE Haptics Symposium (HAPTICS)*. 175–179.

[7] Thomas Augsten, Konstantin Kaefer, René Meusel, Caroline Fetzer, Dorian Kanitz, Thomas Stoff, Torsten Becker, Christian Holz, and Patrick Baudisch. 2010. Multitoe: High-Precision Interaction with Back-Projected Floors Based on High-Resolution Multi-Touch Input. In *Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology (UIST '10)*. Association for Computing Machinery, New York, NY, USA, 209–218. http://dx.doi.org/10.1145/1866029.1866064

[8] Sliman Bensmaïa and Mark Hollins. 2005. Pacinian representations of fine surface texture. *Perception & Psychophysics* 67, 5 (01 Jul 2005), 842–854. http://dx.doi.org/10.3758/BF03193537

[9] Sliman J Bensmaïa and Mark Hollins. 2003. The vibrations of texture. *Somatosensory and Motor Research* 20, 1 (2003), 33–43. http://dx.doi.org/10.1080/0899022031000083825

[10] Wouter M. Bergmann Tiest and Astrid M L Kappers. 2009. Cues for haptic perception of compliance. *IEEE Transactions on Haptics* 2, 4 (2009), 189–199. http://dx.doi.org/10.1109/TOH.2009.16

[11] Christian Corsten, Simon Voelker, Andreas Link, and Jan Borchers. 2018. Use the Force Picker, Luke: Space-Efficient Value Input on Force-Sensitive Mobile Touchscreens. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–12. http://dx.doi.org/10.1145/3173574.3174235

[12] Heather Culbertson, Juliette Unwin, and Katherine J. Kuchenbecker. 2014. Modeling and Rendering Realistic Textures from Unconstrained Tool-Surface Interactions. *IEEE Transactions on Haptics* 7, 3 (July 2014), 381–393. http://dx.doi.org/10.1109/TOH.2014.2316797 Conference Name: IEEE Transactions on Haptics.

[13] Donald Degraen, André Zenner, and Antonio Krüger. 2019. Enhancing Texture Perception in Virtual Reality Using 3D-Printed Hair Structures. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*. ACM Press, Glasgow, Scotland Uk, 1–12. http://dx.doi.org/10.1145/3290605.3300479

[14] C. Doerrer and R. Werthschuetzky. 2002. Simulating Push-Buttons Using a Haptic Display: Requirements on Force Resolution and Force-Displacement Curve. (2002).

[15] Xiaoyan Fu and Dahai Li. 2005. Haptic Shoes: Representing Information by Vibration. In *Proceedings of the 2005 Asia-Pacific Symposium on Information Visualisation - Volume 45 (APVis '05)*. Australian Computer Society, Inc., AUS, 47–50.

[16] Danilo Gallo, Shreepriya Shreepriya, and Jutta Willamowski. 2020. RunAhead: Exploring Head Scanning Based Navigation for Runners. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. http://dx.doi.org/10.1145/3313831.3376828

[17] George A. Gescheider. 1997. *Psychophysics: the fundamentals* (3rd ed ed.). L. Erlbaum Associates, Mahwah, N.J.

[18] Elisa Giaccardi and Elvin Karana. 2015. Foundations of Materials Experience: An Approach for HCI. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2447–2456. http://dx.doi.org/10.1145/2702123.2702337

[19] Bruno L. Giordano and Federico Avanzini. 2014. *Perception and Synthesis of Sound-Generating Materials*. Springer London, London, 49–84. http://dx.doi.org/10.1007/978-1-4471-6533-0_4

[20] Erik Grönvall, Jonas Fritsch, and Anna Vallgårda. 2016. FeltRadio: Sensing and Making Sense of Wireless

Traffic. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16)*. Association for Computing Machinery, New York, NY, USA, 829–840. http://dx.doi.org/10.1145/2901790.2901818

[21] Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jan Borchers, and Jürgen Steimle. 2019. Demonstration of Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–4. http://dx.doi.org/10.1145/3290607.3313255

[22] Seongkook Heo and Geehyuk Lee. 2017. Vibrotactile Compliance Feedback for Tangential Force Interaction. *IEEE Transactions on Haptics* 10, 3 (July 2017), 444–455. http://dx.doi.org/10.1109/TOH.2016.2604305 Conference Name: IEEE Transactions on Haptics.

[23] Seongkook Heo, Jaeyeon Lee, and Daniel Wigdor. 2019. PseudoBend: Producing Haptic Illusions of Stretching, Bending, and Twisting Using Grain Vibrations. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19)*. Association for Computing Machinery, New Orleans, LA, USA, 803–813. http://dx.doi.org/10.1145/3332165.3347941

[24] Erik Hill, Hiroyuki Hatano, Masahiro Fujii, and Yu Watanabe. 2014. Haptic Foot Interface for Language Communication. In *Proceedings of the 5th Augmented Human International Conference (AH '14)*. Association for Computing Machinery, New York, NY, USA, Article Article 9, 4 pages. http://dx.doi.org/10.1145/2582051.2582060

[25] Cedric Honnet, Hannah Perner-Wilson, Marc Teyssier, Bruno Fruchard, Jürgen Steimle, Ana C. Baptista, and Paul Strohmeier. 2020. PolySense: Augmenting Textiles with Electrical Functionality Using In-Situ Polymerization. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. http://dx.doi.org/10.1145/3313831.3376841

[26] Daniel Horodniczy and Jeremy R. Cooperstock. 2017. Free the Hands! Enhanced Target Selection via a Variable-Friction Shoe. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 255–259. http://dx.doi.org/10.1145/3025453.3025625

[27] J. Timothy Inglis, Paul M. Kennedy, Cari Wells, and Romeo Chua. 2002. *The Role of Cutaneous Receptors in the Foot*. Springer US, Boston, MA, 111–117. http://dx.doi.org/10.1007/978-1-4615-0713-0_14

[28] Alexandra Ion, Robert Kovacs, Oliver S. Schneider, Pedro Lopes, and Patrick Baudisch. 2018. Metamaterial Textures. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, Article Paper 336, 12 pages. http://dx.doi.org/10.1145/3173574.3173910

[29] A. Isleyen, Y. Vardar, and C. Basdogan. 2019. Tactile Roughness Perception of Virtual Gratings by Electrovibration. *IEEE Transactions on Haptics* (2019), 1–1.

[30] Mads Møller Jensen and Florian "Floyd" Mueller. 2014. Running with Technology: Where Are We Heading?. In *Proceedings of the 26th Australian Computer-Human Interaction Conference on Designing Futures: The Future of Design (OzCHI '14)*. Association for Computing Machinery, New York, NY, USA, 527–530. http://dx.doi.org/10.1145/2686612.2686696

[31] Roland S Johansson and J Randall Flanagan. 2009. Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience* 10, 5 (2009), 345.

[32] L. A. Jones and H. Z. Tan. 2013. Application of Psychophysical Techniques to Haptic Research. *IEEE Transactions on Haptics* 6, 3 (2013), 268–284.

[33] Elvin Karana, Elisa Giaccardi, Niels Stamhuis, and Jasper Goossensen. 2016. The Tuning of Materials: A Designer's Journey. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16)*. Association for Computing Machinery, New York, NY, USA, 619–631. http://dx.doi.org/10.1145/2901790.2901909

[34] Johan Kildal. 2010. 3D-press: haptic illusion of compliance when pressing on a rigid surface. In *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction on - ICMI-MLMI '10*. ACM Press, Beijing, China, 1. http://dx.doi.org/10.1145/1891903.1891931

[35] Sunjun Kim and Geehyuk Lee. 2013. Haptic Feedback Design for a Virtual Button along Force-Displacement Curves. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology (UIST '13)*. Association for Computing Machinery, New York, NY, USA, 91–96. http://dx.doi.org/10.1145/2501988.2502041

[36] Jaeyeon Lee, Mike Sinclair, Mar Gonzalez-Franco, Eyal Ofek, and Christian Holz. 2019. TORC: A Virtual Reality Controller for In-Hand High-Dexterity Finger Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, Article Paper 71, 13 pages. http://dx.doi.org/10.1145/3290605.3300301

[37] Yi-Chi Liao, Sunjun Kim, Byungjoo Lee, and Antti Oulasvirta. 2020. Button Simulation and Design via FDVV Models. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New

York, NY, USA, 1–14.
http://dx.doi.org/10.1145/3313831.3376262

[38] Yi-Chi Liao, Sunjun Kim, and Antti Oulasvirta. 2018. One Button to Rule Them All: Rendering Arbitrary Force-Displacement Curves. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings (UIST '18 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 111–113. http://dx.doi.org/10.1145/3266037.3266118

[39] Teemu Mäki-patola and Perttu Hämäläinen. 2004. Latency Tolerance for Gesture Controlled Continuous Sound Instrument without Tactile Feedback. *Proceedings of the International Computer Music Conference* 1998 (2004).

[40] Justin Matejka, Michael Glueck, Tovi Grossman, and George Fitzmaurice. 2016. The Effect of Visual Appearance on the Performance of Continuous Sliders and Visual Analogue Scales. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, San Jose California USA, 5421–5432. http://dx.doi.org/10.1145/2858036.2858063

[41] 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. http://dx.doi.org/https://doi.org/10.1016/j.mechatronics.2017.07.005

[42] Fabrizio Mulas, Salvatore Carta, Paolo Pilloni, and Matteo Manca. 2011. Everywhere Run: A Virtual Personal Trainer for Supporting People in Their Running Activity. In *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology (ACE '11)*. Association for Computing Machinery, New York, NY, USA, Article 70, 2 pages. http://dx.doi.org/10.1145/2071423.2071510

[43] Troy Nachtigall, Oscar Tomico, Ron Wakkary, and Pauline van Dongen. 2019. Encoding Materials and Data for Iterative Personalization. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. http://dx.doi.org/10.1145/3290605.3300749

[44] Allen Newell. 1994. *Unified theories of cognition*. Harvard University Press.

[45] Rolf Nordahl, Amir Berrezag, Smilen Dimitrov, Luca Turchet, Vincent Hayward, and Stefania Serafin. 2010. Preliminary Experiment Combining Virtual Reality Haptic Shoes and Audio Synthesis. In *Haptics: Generating and Perceiving Tangible Sensations (Lecture Notes in Computer Science)*, Astrid M. L. Kappers, Jan B. F. van Erp, Wouter M. Bergmann Tiest, and Frans C. T. van der Helm (Eds.). Springer, Berlin, Heidelberg, 123–129. http://dx.doi.org/10.1007/978-3-642-14075-4_18

[46] Marianna Obrist, Sue Ann Seah, and Sriram Subramanian. 2013. Talking about Tactile Experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. Association for Computing Machinery, New York, NY, USA, 1659–1668. http://dx.doi.org/10.1145/2470654.2466220

[47] S. Oh and S. Choi. 2019. Effects of Contact Force and Vibration Frequency on Vibrotactile Sensitivity During Active Touch. *IEEE Transactions on Haptics* 12, 4 (2019), 645–651.

[48] Sujata Pal, Anindo Ghosh, and Vivek Sethi. 2018. Vehicle Air Pollution Monitoring Using IoTs. In *Proceedings of the 16th ACM Conference on Embedded Networked Sensor Systems (SenSys '18)*. Association for Computing Machinery, New York, NY, USA, 400–401. http://dx.doi.org/10.1145/3274783.3275202

[49] Erik Pescara, Florian Dreschner, Karola Marky, Kai Kunze, and Michael Beigl. 2020. GenVibe: Exploration of Interactive Generation of Personal Vibrotactile Patterns. *Augmented Humans* (2020).

[50] Erik Pescara, Michael Hefenbrock, Thomas Rzepka, and Michael Beigl. 2018. Vibration Personalization with Evolutionary Algorithms. In *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers (UbiComp '18)*. Association for Computing Machinery, New York, NY, USA, 436–439. http://dx.doi.org/10.1145/3267305.3267619

[51] Claire Petitmengin. 2006. Describing one's subjective experience in the second person: An interview method for the science of consciousness. *Phenomenology and the Cognitive Sciences* 5, 3-4 (Dec. 2006), 229–269. http://dx.doi.org/10.1007/s11097-006-9022-2

[52] Gonzalo Ramos, Matthew Boulos, and Ravin Balakrishnan. 2004. Pressure widgets. In *Proceedings of the 2004 conference on Human factors in computing systems - CHI '04*. ACM Press, Vienna, Austria, 487–494. http://dx.doi.org/10.1145/985692.985754

[53] Joseph M. Romano and Katherine J. Kuchenbecker. 2012. Creating Realistic Virtual Textures from Contact Acceleration Data. *IEEE Transactions on Haptics* 5, 2 (April 2012), 109–119. http://dx.doi.org/10.1109/TOH.2011.38 Conference Name: IEEE Transactions on Haptics.

[54] Maximilian Schirmer, Johannes Hartmann, Sven Bertel, and Florian Echtler. 2015. Shoe Me the Way: A Shoe-Based Tactile Interface for Eyes-Free Urban Navigation. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '15)*. Association for Computing Machinery, New York, NY, USA, 327–336. http://dx.doi.org/10.1145/2785830.2785832

[55] Dominik Schmidt, Rob Kovacs, Vikram Mehta, Udayan Umapathi, Sven Köhler, Lung-Pan Cheng, and Patrick Baudisch. 2015. Level-Ups: Motorized Stilts That Simulate Stair Steps in Virtual Reality. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2157–2160. http://dx.doi.org/10.1145/2702123.2702253

[56] Henning Schmidt, Stefan Hesse, Rolf Bernhardt, and Jörg Krüger. 2005. HapticWalker—a Novel Haptic Foot Device. *ACM Trans. Appl. Percept.* 2, 2 (April 2005), 166–180. http://dx.doi.org/10.1145/1060581.1060589

[57] Richard A Schmidt, Timothy D Lee, Carolee Winstein, Gabriele Wulf, and Howard N Zelaznik. 2018. *Motor control and learning: A behavioral emphasis*. Human kinetics.

[58] Oliver Schneider, Karon MacLean, Colin Swindells, and Kellogg Booth. 2017. Haptic experience design: What hapticians do and where they need help. *International Journal of Human-Computer Studies* 107 (2017), 5 – 21. http://dx.doi.org/https://doi.org/10.1016/j.ijhcs.2017.04.004 Multisensory Human-Computer Interaction.

[59] Oliver Schneider, Siyan Zhao, and Ali Israr. 2015. *FeelCraft: User-Crafted Tactile Content*. Springer Japan, Tokyo, 253–259. http://dx.doi.org/10.1007/978-4-431-55690-9_47

[60] Oliver S Schneider and Karon E MacLean. 2014. Improvising design with a haptic instrument. In *2014 IEEE Haptics Symposium (HAPTICS)*. IEEE, 327–332.

[61] O. S. Schneider and K. E. MacLean. 2016. Studying design process and example use with Macaron, a web-based vibrotactile effect editor. In *2016 IEEE Haptics Symposium (HAPTICS)*. 52–58.

[62] Oliver S. Schneider, Hasti Seifi, Salma Kashani, Matthew Chun, and Karon E. MacLean. 2016. HapTurk: Crowdsourcing Affective Ratings of Vibrotactile Icons. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. Association for Computing Machinery, New York, NY, USA, 3248–3260. http://dx.doi.org/10.1145/2858036.2858279

[63] H. Seifi, K. Zhang, and K. E. MacLean. 2015. VibViz: Organizing, visualizing and navigating vibration libraries. In *2015 IEEE World Haptics Conference (WHC)*. 254–259.

[64] Jotaro Shigeyama, Takeru Hashimoto, Shigeo Yoshida, Taiju Aoki, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. 2018. Transcalibur: Dynamic 2D Haptic Shape Illusion of Virtual Object by Weight Moving VR Controller. In *ACM SIGGRAPH 2018 Posters (SIGGRAPH '18)*. Association for Computing Machinery, New York, NY, USA, Article 29, 2 pages. http://dx.doi.org/10.1145/3230744.3230804

[65] Advaith Siddharthan and Napoleon Katsos. 2012. Offline Sentence Processing Measures for Testing Readability with Users. In *Proceedings of the First Workshop on Predicting and Improving Text Readability for Target Reader Populations (PITR '12)*. Association for Computational Linguistics, USA, 17–24.

[66] Alexa F. Siu, Mike Sinclair, Robert Kovacs, Eyal Ofek, Christian Holz, and Edward Cutrell. 2020. Virtual Reality Without Vision: A Haptic and Auditory White Cane to Navigate Complex Virtual Worlds. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. http://dx.doi.org/10.1145/3313831.3376353

[67] Paul Strohmeier. 2019. *Shaping Material Experiences — Designing Vibrotactile Feedback for Active Perception*. Ph.D. Dissertation. http://www.embodimentlabs.org/thesis.pdf

[68] Paul Strohmeier, Sebastian Boring, and Kasper Hornbæk. 2018. From Pulse Trains to "Coloring with Vibrations": Motion Mappings for Mid-Air Haptic Textures. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*. ACM Press, Montreal QC, Canada, 1–13. http://dx.doi.org/10.1145/3173574.3173639

[69] Paul Strohmeier, Jesse Burstyn, Juan Pablo Carrascal, Vincent Levesque, and Roel Vertegaal. 2016. ReFlex: A Flexible Smartphone with Active Haptic Feedback for Bend Input. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16)*. Association for Computing Machinery, New York, NY, USA, 185–192. http://dx.doi.org/10.1145/2839462.2839494

[70] Paul Strohmeier and Kasper Hornbæk. 2017. Generating Haptic Textures with a Vibrotactile Actuator. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4994–5005. http://dx.doi.org/10.1145/3025453.3025812

[71] Paul Strohmeier and Jess McIntosh. 2020. Novel Input and Output Opportunities Using an Implanted Magnet. In *Proceedings of the Augmented Humans International Conference (AHs '20)*. Association for Computing Machinery, New York, NY, USA, Article 10, 5 pages. http://dx.doi.org/10.1145/3384657.3384785

[72] Ana Tajadura-Jiménez, Maria Basia, Ophelia Deroy, Merle Fairhurst, Nicolai Marquardt, and Nadia Bianchi-Berthouze. 2015. As Light as Your Footsteps: Altering Walking Sounds to Change Perceived Body Weight, Emotional State and Gait. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2943–2952. http://dx.doi.org/10.1145/2702123.2702374

[73] Oscar Tomico and Danielle Wilde. 2016. Embodying Soft Wearables Research. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded,*

*and Embodied Interaction (TEI '16)*. Association for Computing Machinery, New York, NY, USA, 774–777. http://dx.doi.org/10.1145/2839462.2854115

[74] L. Turchet, P. Burelli, and S. Serafin. 2013. Haptic Feedback for Enhancing Realism of Walking Simulations. *IEEE Transactions on Haptics* 6, 1 (2013), 35–45.

[75] Luca Turchet, Rolf Nordahl, Stefania Serafin, Amir Berrezag, Smilen Dimitrov, and Vincent Hayward. 2010. Audio-haptic physically-based simulation of walking on different grounds. *2010 IEEE International Workshop on Multimedia Signal Processing, MMSP2010* (11 2010), 269 – 273. http://dx.doi.org/10.1109/MMSP.2010.5662031

[76] Jelle Van Dijk. 2018. Designing for Embodied Being-in-the-World: A Critical Analysis of the Concept of Embodiment in the Design of Hybrids. *Multimodal Technologies and Interaction* 2, 1 (2018). http://dx.doi.org/10.3390/mti2010007

[77] Eduardo Velloso, Dominik Schmidt, Jason Alexander, Hans Gellersen, and Andreas Bulling. 2015. The Feet in Human–Computer Interaction: A Survey of Foot-Based Interaction. *ACM Comput. Surv.* 48, 2, Article Article 21 (Sept. 2015), 35 pages. http://dx.doi.org/10.1145/2816455

[78] Ronald T Verrillo. 1962. Effect of Contactor Area on the Vibrotactile Threshold. *The Journal of the Acoustical Society of America* 35, 12 (1962). http://dx.doi.org/10.1121/1.1918868

[79] Yon Visell, Jeremy R. Cooperstock, Bruno L. Giordano, Karmen Franinovic, Alvin Law, Stephen McAdams, Kunal Jathal, and Federico Fontana. 2008. A Vibrotactile Device for Display of Virtual Ground Materials in Walking. In *Haptics: Perception, Devices and Scenarios*, Manuel Ferre (Ed.). Springer Berlin Heidelberg, Berlin, Heidelberg, 420–426.

[80] Y. Visell, A. Law, and J. R. Cooperstock. 2009a. Touch Is Everywhere: Floor Surfaces as Ambient Haptic Interfaces. *IEEE Transactions on Haptics* 2, 3 (2009), 148–159.

[81] Y. Visell, A. Law, and J. R. Cooperstock. 2009b. Toward iconic vibrotactile information display using floor surfaces. In *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. 267–272.

[82] Y. Wang and M. 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.

[83] Y. Wang and M. A. Minor. 2018. Design and Evaluation of a Soft Robotic Smart Shoe for Haptic Terrain Rendering. *IEEE/ASME Transactions on Mechatronics* 23, 6 (2018), 2974–2979.

[84] Junji Watanabe, Hideyuki Ando, and Taro Maeda. 2005. Shoe-Shaped Interface for Inducing a Walking Cycle. In *Proceedings of the 2005 International Conference on Augmented Tele-Existence (ICAT '05)*. Association for Computing Machinery, New York, NY, USA, 30–34. http://dx.doi.org/10.1145/1152399.1152406

[85] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. 2018. Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. http://dx.doi.org/10.1145/3173574.3173660

[86] Peter Williams and Daniel Overholt. 2017. bEADS Extended Actuated Digital Shaker. In *NIME 2017 Proceedings of the International Conference on New Interfaces for Musical Expression*. 13–18. http://homes.create.aau.dk/dano/nime17/papers/0003/paper0003.pdf

[87] Anusha Withana, Daniel Groeger, and Jürgen Steimle. 2018. Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*. Association for Computing Machinery, New York, NY, USA, 365–378. http://dx.doi.org/10.1145/3242587.3242645

[88] Emma Witkowski. 2013. Running from Zombies. In *Proceedings of The 9th Australasian Conference on Interactive Entertainment: Matters of Life and Death (IE '13)*. Association for Computing Machinery, New York, NY, USA, Article 1, 8 pages. http://dx.doi.org/10.1145/2513002.2513573

[89] Hsin-yun Yao and Vincent Hayward. 2006. An experiment on length perception with a virtual rolling stone. In *Proceedings of Eurohaptics*. 325–330.

[90] André Zenner and Antonio Krüger. 2019. Drag:On: A Virtual Reality Controller Providing Haptic Feedback Based on Drag and Weight Shift. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. http://dx.doi.org/10.1145/3290605.3300441

[91] Shumin Zhai. 1995. *Human Performance in Six Degree of Freedom Input Control*. Ph.D. Dissertation.