FeetThrough: Electrotactile Foot Interface that Preserves Real-World Sensations

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Figure 1: We argue that foot haptic interfaces should optimize for what users feel during output and prioritize *letting users feel the terrain under their feet.* Feeling ground features with our soles is critical for balance on uneven terrains and stairs. In this paper, we demonstrate that electrotactile stimulation not only achieves an improved "feel-through" of terrains compared to traditional vibrotactile foot interfaces but also lets users feel the output more clearly (lower two-point discrimination threshold).

ABSTRACT

Haptic interfaces have been extended to the feet to enhance foot-based activities, such as guidance while walking or stepping on virtual textures. Most feet haptics use mechanical actuators, namely vibration motors. However, we argue that vibration motors are not the ideal actuators for all feet haptics. Instead, we demonstrate that electrotactile stimulation provides qualities that make it a powerful feet-haptic interface: (1) Users wearing electrotactile can not only feel the stimulation but can also *better feel the terrain under their feet*—this is critical as our feet are also responsible for the balance on uneven terrains and stairs—electrotactile achieves this improved "feel-through" effect because it is thinner than vibrotactile actuators, at 0.1 mm in our prototype; (2) While a single vibrotactile actuator will also vibrate surrounding skin areas, we found improved two-point discrimination thresholds for electrotactile; (3) Electrotactile can be applied directly to soles, insoles or socks, enabling new applications such as barefoot interactive experiences or without requiring users to have custom-shoes with built-in vibration motors. Finally, we demonstrate applications in which electrotactile feet interfaces allow users to feel not only virtual information but also the real terrain under their shoes, such as a VR experience where users walk on ground props and a tactile navigation system that augments the ground with virtual tactile paving to assist pedestrians in low-vision situations.

CCS CONCEPTS

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

KEYWORDS

Haptics, electrotactile, foot, feel-through, VR, AR

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1 INTRODUCTION

Haptic interfaces have been extended to the user's feet in order to enhance foot-based activities, such as guidance while walking [4, 38, 56], feeling virtual textures [50, 52, 57], pose correction [7, 8], and more. Most contemporary haptic interfaces for the feet

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consist of mechanical actuators, particularly *vibration motors*. This is understandable since this type of haptic actuator has proven useful for many hand-based haptic interfaces, such as vibration gloves [1] or finger haptics [41], and is relatively easy to embed inside shoe insoles [37, 62], even including in larger arrays [38, 56].

However, we argue that vibration motors *are not the ideal actuators for all feet haptics*. While vibration motors will excel at applications that render textures to the user's feet (e.g., [50, 62]), we argue, and demonstrate in this paper, that this is not the case for any applications in which the user not only need to care about feeling the output from the haptic interface but also *feeling the terrain* under their feet. Our feet soles play a considerable role in our sense of balance in uneven terrains, stairs, and other ground obstacles [27, 51]. This has especially been linked to the tactile senses in our soles, as denoted by Viseux in their comprehensive review "(...) cutaneous afferents in the foot contribute to our ability to stand upright" [58]. In fact, the author goes further and denotes: "(...) decline in sensitivity is frequently associated with poorer postural control and *increased risk of falls*" [58]—we argue that designing most haptic foot interfaces using thick mechanical actuators risks bringing users into this situation as the thickness of the actuator will limit the tactile perception, in other words, the actuator "filters out" the ground's tactile features (Figure 1).

To tackle this, we propose a turn in haptic interfaces for the feet by exploring electrotactile stimulation. In this paper, we demonstrate, through a series of user studies, three key advantages of electrotactile foot stimulation over vibrotactile stimulation. In particular: (1) Unlike with vibration motors, a user wearing our electrotactile *FeetThrough* prototype can not only feel the haptic stimulation (e.g., shapes for guidance while walking) but can also better feel the terrain under their feet, which was validated in our Study 2—electrotactile electrode arrays achieve this "feel-through" effect better because they are inherently thinner (0.1 mm in our *FeetThrough* prototype) than an array made with mechanical actuators. (2) While in vibrotactile stimulation, a single actuator will also vibrate surrounding areas (crosstalk), we found this is not the case with electrotactile stimulation to the feet and found that it provides superior two-point discrimination thresholds, which was validated our Study 1; (3) We also found that, due to its flexibility, electrotactile arrays are easier to apply to several interactive contexts, including some cases in which vibration motors are mostly impractical. Such as barefoot interactive experiences—users would step on the vibration motor's case and find their entire body's weight distributed into a few uncomfortable, high-pressure points. Moreover, electrotactile interfaces can be applied directly to the soles (or in a sock form factor) and thus perform without customized shoes, as is the case with embedding vibration motors in the insole.

Finally, we demonstrate applications in which electrotactile feet interfaces allow users to feel not only virtual information but also the real terrain under their shoes, such as a VR experience where users walk on ground props and a tactile navigation system that augments the ground with virtual tactile paving to assist pedestrians who are visually impaired.

2 RELATED WORK

The work presented in this paper builds primarily on the field of haptics, with particular emphasis on *tactile* haptic interfaces for the feet. Moreover, since our primary goal is engineering a tactile feet interface that allows users to still feel the terrain under their feet, we take inspiration from research exploring this goal for the fingerpad. Finally, as our approach uses electrotactile stimulation on the sole, we succinctly review the field of electrotactile, which has explored chiefly other skin areas, especially fingerpads.

2.1 Majority of tactile foot haptic interfaces use vibrations

In recent years, haptic interfaces have been extended to the feet to enhance foot-based activities, such as navigation [4, 25, 38, 47, 56, 63], information (e.g., safety information [34], awareness of surroundings [20, 32], sensory substitution [6], music rhythm [42]), foot I/O devices [3, 44], language communication [25], walking [19, 33, 37, 62, 65, 67], and rendering the feel of virtual surfaces [40, 50, 52, 55, 57].

While the choice of actuators for feet haptics differs based on the intended purposes, most feet haptic devices rely on mechanical stimulation, especially using *vibration motors*—usually eccentric rotating mass motors or linear resonant actuators. While other mechanical actuators, such as brakes [54], inflatables [14], or fluids [49], have been used in foot stimulation, these are less popular than vibrotactile actuators for feet. This popularity is likely a consequence of the small size & ease of use of vibration motors, as well as the widespread use for tactile stimulation of fingers and hands—the largest area of haptics research.

Implementing feet haptics with vibration. The canonical implementation of the most vibration-based feet haptics is *embedding* vibration motors under the sole or inside insoles. Some devices have vibrators installed in shoes rather than under the sole. *GymSoles* [7, 8] used eight vibrators around the foot to realize posture feedback for assisting squats and dead-lifts. *Pace-sync* shoe [60] and devices for helping training [5, 9] used vibrators placed on an instep or an ankle to notify the timing and training states—these employ vibration as a notification. In such instances, providing haptic feedback to areas other than the soles is sufficient for notifications or symbolic information. Yet, our soles have the same type of skin receptors as our hands [51] and, as such, pose an excellent target for stimulation with a higher number of points (e.g., as in most haptic displays for realism).

While vibrators are well suited to simulate stepping on virtual ground textures, it is challenging to present *static* information or *shapes* because vibrations are also propagated via the housing of the device and via the surrounding skin. Hill et al. engineered a foot device using multiple vibrators for language communication. However, they needed to adopt a sequential stimulation because vibrations *can be confused if presented simultaneously* [15]. This issue can be seen in other works and was typically handled by driving vibrators sequentially [6, 28, 56] or by spacing vibrators further away to minimize inter-vibrator crosstalk [45].

More importantly, we argue that conventional wearable foot interfaces usually cover the sole with rigid devices and do not consider the importance of *letting users feel the terrain*. One example technique that avoids direct placement of vibrators in the soles uses a toenail vibration illusion [17, 46] (inspired by an approach of fingernail vibration illusion [2]). However, the region that can be stimulated is very limited, and the resolution is insufficient to depict shapes and more.

2.2 Feel-through haptic devices for the finger

The problem of haptic actuators blocking real-world sensations has sparked recent interest for researchers that work in hand-based interactions for AR/MR because, in these contexts, users need not only to touch virtual objects (e.g., AR buttons) but physical objects (e.g., tools or props). A canonical example is *Tacttoo* [61], which attaches electrodes to the user's fingerpad and can simultaneously preserve some macro-features of the touched objects. As demonstrated in the experiments of *Like a Second Skin* [39], it is possible to "feel through," to some extent, while one's skin is covered by a device made from a thin film—in fact, the thinner the film, the less it obstructs feeling the real world. Similarly, *Hydroring* [13] also aimed to preserve the haptic perception of the physical world, but instead, wrapped the user's finger in a soft actuator where liquids can flow through—its softness allows users to still feel through the device to some extent. We take inspiration from these works that promote feel-through for the fingerpad but explore how to achieve this in the case of foot haptics.

2.3 Importance of feeling physical terrain under our feet

Sensory feedback from the sole plays a crucial role in gait control, balance, and maneuvering around uneven terrains and other ground obstacles [27, 51]. This has especially been linked to the tactile information acquired by the skin of our soles as we walk around [58]. Strzalkowski et al. make a similar argument for the role of tactile sensations originating at the sole in walking movements and gait patterns "(. . .) *feedback associated with standing balance are conveyed by cutaneous afferents into the CNS [central nervous system], where it interacts with descending motor commands*" [51]. Viseux also highlights that when our ability to feel foot sensations deteriorates, which occurs naturally with age with a number of neurological disorders, it "(...) is frequently associated with poorer postural control and *increased risk of falls*" [58]. We argue that this key role of our soles should be a guiding factor in developing new haptic interfaces for the feet—we stress the importance of engineering devices that preserve real-world sensations.

2.4 Electrotactile stimulation

Many researchers have explored electrical stimulation to realize haptics without mechanical parts. Moreover, because electrodes can be typically made smaller than a mechanical actuator (which requires physical displacement and that requires space), these electrotactile arrays have also been heavily explored for higher spatial resolution (e.g., [24, 35]).

Electrotactile stimulation has been chiefly used for hands and fingers, such as for textures [12, 64], delivering sensory substitution for prostheses [11, 30], or touch information in virtual environments [59]. While most of the electrotactile stimulation has been applied on the fingers and hands, some researchers in medicine & neuroscience have also confirmed its feasibility to stimulate the soles. These researchers used electrotactile stimulation of the soles as either a way to investigate the role of afferents from the sole in walking [66] or to quantify the feet's tactile receptors [10]—the latter measurements by Frahm et al. found that sensations at the heel were milder than at other sites and that the foot arch was a more sensitive area. Solomonow et al. reported a two-point electrical stimulation discrimination threshold on the sole's arch at 7.67 mm [48]. We take inspiration from this but advance it by investigating these thresholds at three sole regions since they did not survey it.

3 CONTRIBUTION, BENEFITS, AND LIMITATIONS

Our key contribution is the concept that foot haptic interfaces can be designed to render haptic sensations and *let users feel the terrain under their feet*. For this, we proposed a turn from the more traditional vibration-based foot haptics to electrotactile actuation. By means of two studies, our *FeetThrough* prototype and its applications, we demonstrate three key benefits of this approach to feet haptics: (1) Users wearing electrotactile can not only feel the stimulation but can also better feel shapes under their feet—this is critical as our feet are also responsible for balance on uneven terrains and stairs—electrotactile achieves this improved "feel-through" effect because it is thinner than vibrotactile actuators, at 0.1 mm in our prototype; (2) While a single vibrotactile actuator will also vibrate surrounding skin areas, we found improved two-point discrimination thresholds for electrotactile; (3) Electrotactile can be applied directly to soles, insoles or socks, enabling new applications such as barefoot interactive experiences or without requiring users to have custom-shoes with built-in vibration motors.

Electrotactile is not without limitations: (1) electrotactile has not been shown to rival vibration regarding texture rendering; and (2) as any other technique based on electrical stimulation, it requires the attachment of electrodes to the skin and calibration. However, we argue that the benefits can outweigh some limitations as our studies demonstrate that participants could better discriminate electrotactile stimulation than vibrations and better feel shapes under their feet. We think of this work as a first step into prioritizing letting users feel the ground beneath their soles with haptic feedback.

4 IMPLEMENTATION

To help readers replicate our *FeetThrough* prototype, we now provide the necessary technical details. Additionally, all source codes and materials are made publicly available.[1]

4.1 Electrode layout

We developed a flexible electrode array with 60 electrodes that cover the sole from the ball to the heel (Figure 2).

While one can apply this technique to any region of the foot, we opted not to extend the electrodes to the toes for two reasons: (1) since our goal is to *balance* feeling the terrain under one's foot and haptic stimulation, we opted to let the toes be free and available to adjust the sole while stepping—toes have a crucial role in walking [16]; moreover, (2) toes are joints, unlike the fairly smooth and

[1] http://lab.plopes.org/#FeetThrough

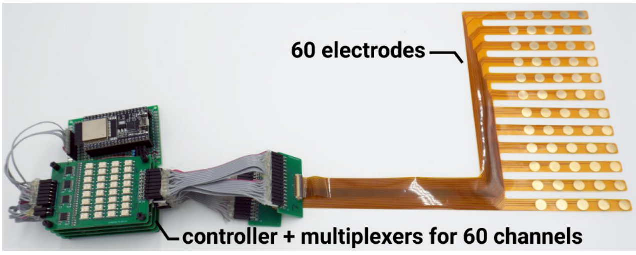

Figure 2: A prototype of electrodes and stimulation devices.

continuous surface of the sole, which would make the electrode attachment more difficult. Future work might certainly explore extending our device to toes to investigate new variations.

As for our electrode design, electrodes are 8 mm in diameter and separated by 15 mm (center-to-center). This diameter is based on the sole's receptive fields of skin receptors (SA I and FA I) [51]. This relatively larger diameter than the canonical electrodes for fingers worked to avoid any pain that could be induced due to small electrodes [21, 30].

4.2 Electrode arrays on a flexPCB

To keep our electrode arrays sturdy enough that users can step on them and remain as flexible and thin as possible to feel the macro-features of terrain, we opted for fabricating these as flexible PCBs (flexPCB). While other techniques are possible, such as screen-printing (e.g., as used in [61]), copper tape (e.g., as used in [18, 26]) or even the traditional pre-gelled electrodes (e.g., as used in [21, 23, 48]), the flexPCB substrate is very strong (e.g., hard to rip) compared to these prior techniques, while still being relatively thin at 0.1 mm, striking a balance in terms of being thin and durable. The substrate used in our flexible PCBs was made from polyimide, and the electrodes were copper coated with immersion gold (ENIG)—these materials are commonly used for electrotactile displays [11] or even featured in intra-oral electrotactile displays [53].

4.3 Stimulation parameters

We used an AC square waveform (biphasic stimulation) with a pulse width of 250 μs and a 100 μs gap between two phases. Stimulation frequency was set to 50 Hz for studies. These pulse width and frequency were decided based on previous work [23, 30]. Furthermore, Solomonow et al. [48] reported the lowest two-point discrimination threshold was observed at around 50 Hz. We opted for AC stimulation since the skin of the sole is thicker than many other parts (e.g., fingers), and AC stimulation is known to be effective for tactile sensations in these conditions [30], which we confirmed in our early pilots. The stimulation intensity was always set per user to ensure pain-free operation. To illustrate its magnitude, the average amplitude for participants was 8.6 mA (SD=5.5 mA) in Study 1 (maximum intensity, no pain) and 5.0 mA (SD=1.7 mA) in Study 2 (noticeable sensation threshold).

4.4 Stimulation multiplexer circuitry

Figure 3 depicts the multiplexer circuit that we engineered to select which electrodes are utilized. Our electrotactile array can be driven by an existing electrical stimulator. We utilized the medically-compliant stimulator RehaStim (often used in electrical interfaces, e.g., [18]), but any other electrical stimulator is compatible (e.g., [22]). Our multiplexer is responsible for selecting which electrode channels output the stimulator's waveforms. Note that our stimulator is not a strict 1:N, in which one input is distributed to only *one* of N possible outputs. Instead, we implemented our stimulator to allow one input to be distributed to *any number* of the N output channels, i.e., it can deliver the input to multiple channels simultaneously. In total our multiplexer can deliver stimulation to 60 channels for one foot.

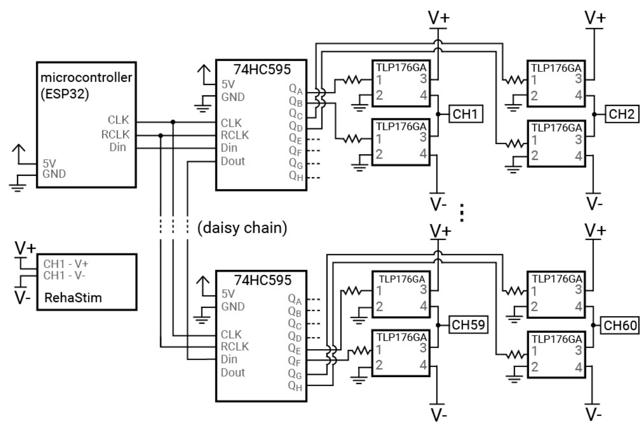

Figure 3: Our multiplexer circuit for 60 channels.

At every electrode, we added a half-bridge circuit with two TLP176 MOSFET high-voltage photorelays, which allows our device to select whether this electrode is connected to the negative or positive side of the stimulator —thus, all channels can be freely routed. To control all 60 photorelays, we utilize 16 SN74HC595 8-bit shift registers, which are controlled by our microcontroller, an ESP32 DevKit-C. Moreover, our device needs 1 ms at maximum to reroute all stimulation channels. Finally, we manufactured two complete devices in our AR/VR applications (Figure 14 and Figure 15) to stimulate both feet.

4.5 Electrical stimulation method

As typical in electrotactile stimulation, we use time-division multiplexing via fast-switching (1 ms) of the stimulated point to present concurrent stimulations [23]. We connected only the surrounding electrodes of the positive electrode (the stimulation point) to the negative channel to concentrate the current around the stimulation point. Figure 4 illustrates an example of a stimulation pattern in Study 1. Stimulation is delivered to each of the two points sequentially by time-multiplexing. Our stimulation frequency is set at 50 Hz and a maximum of 12 simultaneous points to account for the full round-trip latency of the multiplexer (1 ms to change the stimulation point, 600 μs of stimulation, rotate by 60 points). For example, our device can stimulate up to 12 points for 50 Hz. However, we can also stimulate all 60 points simultaneously, instead, at 10 Hz.

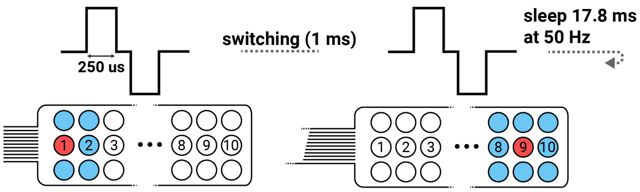

Figure 4: We use time-division multiplexing for multi-point stimulation.

4.6 Alternatives for wearing our device

In Figure 5, we illustrate several approaches for attaching our electrode array to the user's soles, arranged in order of increasing ease of use. In this paper, we explored and studied the attachment depicted in Figure 5 (a), which uses skin-safe medical tapes, resulting in a strong coupling between electrodes and skin. However, other alternatives can be explored depending on the design goal. Figure 5 (b) depicts how the electrodes can also be attached to the sole using custom double-sided tapes with holes for the electrodes. It is worth noting that while the aforementioned (a) and (b) approaches are less convenient since they require an attachment, they allow for unique applications not possible before, i.e., *feet haptics while barefoot*, which we later take advantage of in two of our applications. Further, two methods can provide additional ease of use: (c) stitching electrodes in a sock and (d) lining the insole of the shoe with electrodes while users are barefoot—these latter methods allow users to put/remove the device rapidly and effortlessly. Finally, it is worth noting that further investigations are necessary to explore all these alternative approaches.

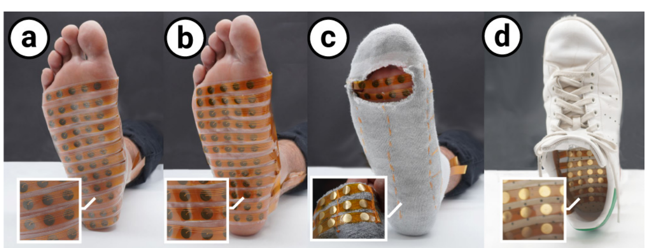

Figure 5: Four possible attachment techniques.

4.7 Application-specific implementations

Figure 6 illustrates the key hardware components attached to the user's feet, not including headsets used for AR/VR. To track foot positions in VR, we employed HTC VIVE trackers. For AR navigation, we used HoloLens 2 to estimate coarse foot positions based on head position (provided by HoloLens' room tracking). For posture feedback, we attached four FSR-based pressure sensors to each sole corner.

In VR/AR applications, the stimulator and a laptop are worn in a backpack. AR and VR applications run on a separate computer, and stimulation commands are transmitted to the laptop via OSC. Finally, the pressure sensor values are sampled via the same microcontroller used for multiplexing.

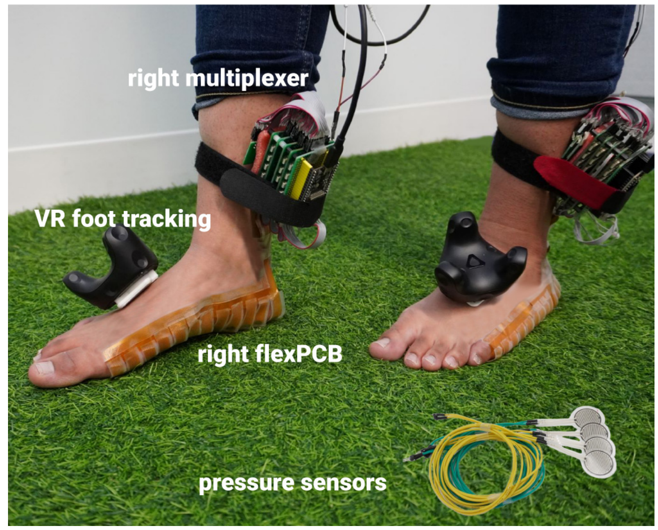

Figure 6: Key hardware attached to the user's feet: one of flexPCB with 60 electrodes for each foot, a multiplexer unit for each electrode array, tracking for any VR application, and four pressure sensors (FSR) worn at the sole for balance detection.

5 USER STUDIES

We conducted two user studies to validate the benefits of switching from vibrotactile to electrotactile foot stimulation. To the best of our knowledge, our studies are the first to explore electrotactile stimulation while *stepping on electrodes* and *physical shapes*. **In our first study**, we assessed whether electrotactile stimulation was easier to spatially distinguish than vibrotactile stimulation through the canonical two-point discrimination study. We found that participants could distinguish electrotactile stimulations at half the distance needed for vibrotactile (effectively double the perceived resolution, i.e., half two-point discrimination). **In our second study,** we measured participants' ability to discriminate two *simultaneous* shapes while they stepped on them, one shape rendered via stimulation and one physical shape. We found that by using electrotactile stimulation, participants could better identify *both* shapes.

5.1 Study 1: Two-point discrimination while standing

The two-point discrimination threshold is one of the canonical criteria when investigating tactile sensations. While previous studies have investigated two-point discrimination thresholds for vibrotactile and electrotactile stimuli, there has been a lack of investigation into these thresholds while standing on the actuators (i.e., pressing electrodes/vibration motors). Such investigation is needed to design vibrotactile/electrotactile devices that provide interactive experiences. Regarding electrotactile stimulus, although Solomonow et al. [48] measured the threshold on the middle of the sole, it is crucial to explore discrimination thresholds at other regions of the feet (e.g., ball and heel), which contact more with the floor or objects than the middle of the sole. Thus, we investigated discrimination thresholds across the entire sole via a standard staircase design to compare the discrimination capabilities of electrical and vibratory stimulation on the sole while *standing on* the haptic feedback devices. This study was approved by our Institutional Review Board (IRB21-1229).

Hypothesis. We posited that the two-point discrimination threshold for electrotactile would be lower since electrical stimulation does not propagate omnidirectionally inside the body as vibration does.

Conditions. Participants experienced two stimulation conditions: **electrotactile** and **vibrotactile**. Moreover, we measured the two-point discrimination in three-foot areas since the sole is heterogeneous [51]. Thus, per condition, participants experienced stimulation to three sole segments: ball (the skin area just below the toes), arch (middle of the foot), and the heel. The order (two stimulation conditions × three regions) was randomized per participant.

Apparatus. Figure 7 depicts the apparatus at the example of the ball location; these devices were applied to all three locations, one location at a time.

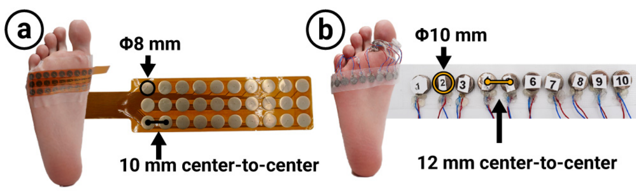

Figure 7: Apparatus used for Study 1 (shown at the ball).

In the electrotactile condition, we used our device as described in *Implementation*, with a three-by-ten electrode array, with an 8 mm diameter and 2 mm gap, as depicted in Figure 7 (a). The electrode diameter was selected based on the receptive field of skin receptors [51]. Note that only the electrodes in the center row were used as the positive electrode of the electrical waveform. In contrast, the electrodes on the top and bottom rows were used as ground (see *Implementation*). Similarly, in the vibrotactile condition, ten vibrators were arranged in line with 2 mm gaps, as depicted in Figure 7 (b). We utilized a 10 mm diameter LRA (C10-100, *Precision Microdrives*) based on prior work [56], driven at its resonant frequency at 175 Hz and at nominal voltage, to output peak performance. Vibrators were driven by a multiplexer similar to the one we engineered for electrotactile stimulation but using 2N3904 NPN transistors, which were, in turn, connected to LTC1660 digital-to-analog converters. Any stimulation, either vibration or electrotactile, was applied for 500 ms.

In early pilots, the authors determined the stimulation frequency and configuration (center-to-center distance and diameter) that elicited the most vivid sensations for both electrotactile and vibrotactile interfaces—enabling a fair comparison for both conditions (i.e., both selected at their top performance). For the frequency, we employed 50 Hz electrotactile stimulation and 175 Hz vibrotactile stimulation, which were selected based on prior work. Solomonow et al. [48] reported the best discrimination ability at 50 Hz for electrotactile stimulus, while Kowalzik et al. [31] reported it at 200 Hz for vibrotactile stimulus. However, LRAs have a fixed resonant frequency, and their performance decreases when actuated outside of it. Thus, we actuate our LRAs at 175 Hz, as close as possible to [31]. Finally, electrodes and vibration motors were arranged with a 2 mm gap because we found slight alternations in the electrode gap changed the vividness and comfort of the sensation, possibly caused by the thick skin of the sole and the difference in current density [21, 30].

Calibration. Before any stimulation, the number of electrodes/vibrators used for each region in the measurement was adjusted based on the foot size of the participant. The electrodes or vibrators were attached to the sole with flexible tapes (to minimize the propagation of vibration), and participants stepped on a silicone pad to ensure the attachment and further minimize the propagation of vibration (Figure 8). Before the trials, the intensities of the electrical stimulation at each point were calibrated (maximum intensity without any pain sensations nor any discomfort).

Figure 8: The study setup. Participants stand on the (a) electrodes or (b) vibrators and a silicone pad.

Study procedure. We utilized the canonical *1-up and 2-down staircase method* to measure two-point discrimination thresholds. One descending series was carried out in each condition from the most distant set of stimulation points, which are on the left and right edges of the sole. Participants answered whether they felt two unique stimulation points, and the staircase proceeded accordingly to their answers until three reversals were observed. As typical of this design, the average value of these reversal points was the outcome of a staircase run (calculated distance was center-to-center).

Since multiple stimulation point sets share equal distances (e.g., with distance=2, sets include (#1, #3), (#2, #4), (#3, #5), etc.), electrodes and vibrators were randomly selected for each trial to randomize stimulation sites and mitigate memorization effects, making the task harder & more robust.

Participants. We recruited twelve participants (eight identified as male, three as female, one did not identify, average age = 24.9 years, SD=3.3, all right-foot dominant) from our local institution. This study took about 30 minutes to complete. Participants received $10 as compensation.

Result. The main result is depicted in Figure 9. The average thresholds of electrical stimulation were 30 mm (ball region), 32 mm (arch region), 26 mm (heel region), and 29 mm (average). Instead, in the vibration condition, most participants could not discriminate vibratory stimulation well—we later illustrate this in detail by computing the normalized to each participant's sole width. A Two-way repeated measures ANOVA was conducted and the assumption of sphericity was not violated. The analysis revealed significant differences with a 5% significance level in the main effects (stimulation condition: $F\ (1, 11) = 106.19$, $p < 0.001$, region condition: $F\ (2, 22) = 8.90$, $p = 0.001$) and the interaction effect ($F\ (2, 22) = 3.67$, $p = 0.042$). Post-hoc analysis with the Bonferroni method found significant differences between vibration and electrical stimulation for each region (ball: $p < 0.001$, arch: $p < 0.001$, heel: $p < 0.001$).

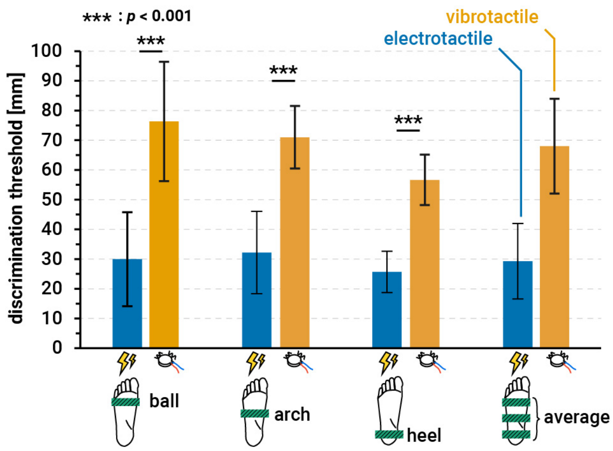

Figure 9: Two-point discrimination thresholds for each region while standing on actuators. Error bars mean standard errors.

Qualitative feedback. Participants voiced qualitative feedback, which we transcribed throughout all trials. Eight participants (out of 12) verbally commented that they felt that the electrotactile stimulation induced precise point sensations, and they felt confident of the stimulus location. Moreover, eight participants (out of 12) voiced difficulties locating positions via vibrotactile; to quote one participant, "vibration feels spread out."

Discussion. The result of the electrotactile was significantly better than the vibrotactile. The discrimination thresholds were nearly consistent in three regions, allowing each sole region to be stimulated with the same electrode density despite the nonuniform distribution of skin receptors in the sole [51]. We also conducted two-way repeated measures ANOVA with normalized data (i.e., normalizing each participant's two-point threshold with their own foot width), and the assumption of sphericity was not violated. Both main effects are also statistically significant (stimuli: $F\ (1, 11) = 95.499$, $p < 0.001$; region: $F\ (2, 22) = 3.721$, $p = 0.041$), but the interaction effects were not significant ($F\ (2, 22) = 0.732$, $p = 0.492$). This is because most participants did not discriminate between the two points during the vibration condition (despite the maximum distance). Altogether, these results suggest that our hypothesis was supported.

Finally, the results of our vibrotactile condition were different from the data reported by Kowalzik et al. [31], in which the thresholds ranged from 15-34 mm. This is likely because our study setup and conditions differ dramatically from theirs. Kowalzik et al. used *two very fine wires* (1 mm) to transmit vibration to the sole of participants *lying on a bed*—not actively *stepping*; this propagates vibrations even more, worsening perception and, thus, the threshold increases. Secondly, the results of our electrotactile condition also differ from those reported by Solomonow et al., found to be ~8 mm [48]. Just as in the previous case, this is also because our setup and conditions differ from theirs. In addition to that, the discrimination threshold for electrotactile differs based on stimulation methods [30], and Solomonow et al. utilized concentric electrodes while we adopted the traditional matrix of electrodes typical in most interactive uses of electrotactile.

5.2 Study 2: Feeling-through while standing on virtual & real

In Study 2, participants were asked to identify shapes presented physically and virtually on the sole simultaneously. Although previous studies [50, 62] examined the modulation of ground stiffness, the impact of actuator choice (the traditional vibrotactile vs. electrotactile) on the perception of *physical* haptic cues has not been investigated, which is also essential as users will be feeling not only on virtual information but also the actual ground under their feet. This study was conducted to (1) explore how well participants can recognize information presented by vibrotactile or electrotactile stimulation and (2) investigate how electrodes and vibration motors interfere with the feel-through perception while stimulations are presented.

Hypothesis. We hypothesized that participants would recognize both physical and virtual shapes under electrical stimulation better than the vibration due to the thin form factor of the electrodes compared to vibration arrays.

Apparatus. We used the same stimulators from Study 1. The electrode and vibration arrays were upgraded to a matrix arrangement to present 2D shapes. We used the design from Velázquez et al. [56], in which 10 mm vibrators were placed in a four-by-four matrix with 7 mm interspaces. The size of the electrodes was 10 mm (the same as vibrators). Electrical stimulation was delivered in the same way as in Study 1. Moreover, to improve vibration transmission to the skin, we attached small protruding drops on top of the vibrators [56]. To compare and measure the impact of two stimulation methods (electrotactile vs. vibrotactile) on the perception, this study was conducted with the barefoot condition (i.e., without the impact of a particular shoe material).

Shapes. Four types of 3d-printed *physical* shapes were prepared, as depicted in Figure 10. We decided to use a subset of the shapes used in Velázquez et al.'s design [56], namely: circle, right "arrow," left "arrow," and vertical line, since these can be used for simple haptic navigation. The size of the physical shapes was 50 × 50 mm, the same size as the actuator matrix, and the height was 5 mm. Finally, the virtual shapes (rendered by either vibration or electrotactile) were the same (same location, shape, and size).

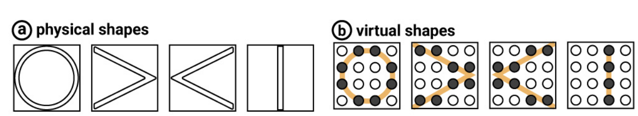

Figure 10: (a) Physical and (b) virtual shapes—a subset of shapes from the identification study by Velázquez et al. [56].

Study procedure. As common in these study designs (e.g., [43], prior to stimulation trials, a practice round was conducted, in which participants stepped on the practice shape without any stimulation and answered what the shape was from our shape list. This was repeated until participants reached a 90% correct answer ratio—now, the trials began. During the trials, participants stepped on a physical shape placed by an experimenter when they heard a first beep and lifted their foot when they listened to a second beep. Simultaneously, while pressing against the shape, they felt the stimulation that presented the virtual shape.

Participants. We recruited twelve participants (five identified as male, six as female, one did not identify, average age=24.8 years, SD=3.4, all right-foot dominant) from our local institution. Seven of them also participated in Study 1. This study took about 1.5 hours to complete. Participants were compensated with $10 for their time.

Results. The correct answer ratio of physical and virtual shapes is shown in Figure 11. Importantly, note that the *chance level* of getting both shapes correct is only 6.25 % (a difficult task since it has 16 possible combinations of the four shapes). The *chance level* for correcting one of the shapes (e.g., physical or virtual) is 25% (four shapes). Overall, participants were above the chance level on all conditions. We conducted two-way repeated measures ANOVA. The assumption of sphericity was violated only for the interaction effect ($p < 0.001$, Greenhouse-Geisser $\epsilon = 0.562$). The main effects of stimulation and shape conditions were significant (stimulation: F (1, 11) = 37.046, $p < 0.001$; shape type: F (2, 22) = 73.548, $p < 0.001$). On the other hand, the interaction effect was not significant (F (1.12, 12.37) = 0.349, $p = 0.59$, computed with Greenhouse-Geisser correction); thus, we did not conduct a post-hoc analysis. Both significant main effects indicate that vibration was considerably less effective than electrical stimulation for identifying physical and virtual shapes. The results revealed that with electrotactile, participants doubled their recognition ability for recognizing *two simultaneous shapes* with an average accuracy of 47% (SD=13%), compared to a much lower ability with vibrotactile (M-26% (SD=11%)).

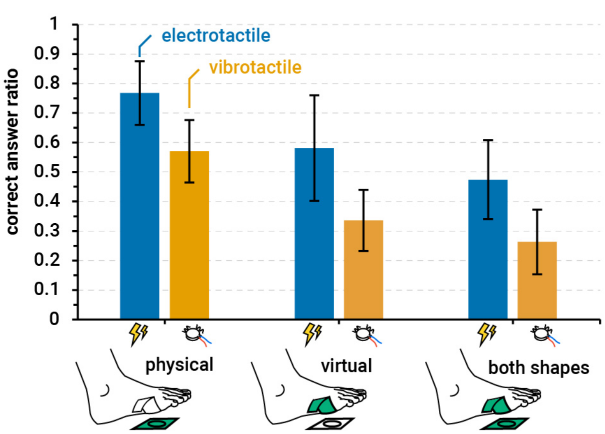

Figure 11: The correct ratio of physical and virtual shapes for each stimulation. The ratio of correctly answering both shapes is also shown. The error bars represent standard errors.

Moreover, the confusion matrices of physical and virtual shapes under each condition are also shown in Figure 12. These follow the same trend as the results above, depicting more accuracy in shape recognition via electrotactile.

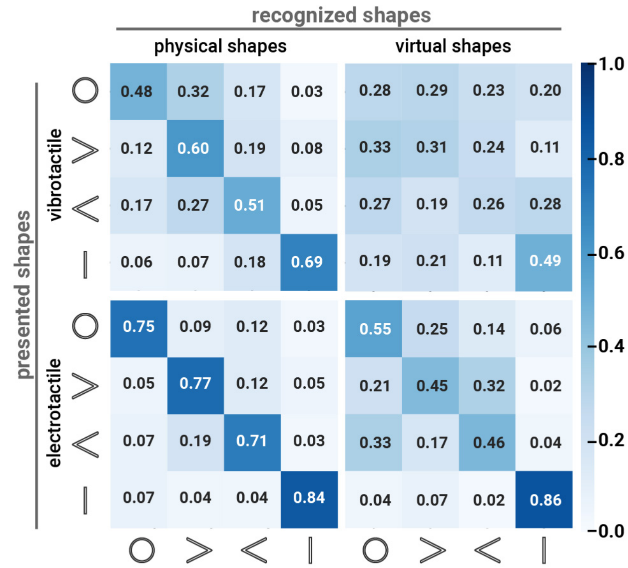

Figure 12: Confusion matrix of both shapes in both conditions.

Qualitative feedback. Participants voiced qualitative feedback, which we transcribed throughout all trials. Ten participants (out of 12) commented that they found it easier to feel virtual shapes via electrotactile than vibrotactile stimulation. In fact, five participants (out of 12) even went as far as to state that vibration did not "feel like any specific shape" (as one put it), leading them to "empty guesses."

Discussion. Overall, these results confirm our hypothesis. However, it is also worth noting that we observed the limits of electrotactile, with some shapes being more easily confused with others (namely those with more segments or acute angles). Moreover, some participants verbally noted they could not recognize the virtual shapes under the vibration condition. On the other hand, most participants recognized virtual shapes under the electrotactile condition. This inferior performance of the vibration condition is consistent with the findings of Velázquez et al. [56]. They noted that integrating many actuators would be pointless if the foot cannot accurately discern which one is vibrating and concluded (like many) that they should be operated sequentially to deliver information using vibrotactile effectively [15, 45]. In contrast, electrotactile stimulation can produce distinguishable shape sensations without relying on sequential actuation.

6 ENVISIONED USE-CASES

Having validated that switching from the vibrotactile to electrotactile allowed users to better feel the terrain under their feet, we envision three use cases in which our *FeetThrough* device might provide interactive benefits compared to traditional vibrotactile: (1) VR feedback while stepping on ground props, (2) feedback for postural control in yoga, and (3) as a haptic cue for walking navigation.

6.1 Use-case 1: Feeling Virtual Sensations and Foot Props

Figure 13 depicts a sequence of a barefoot VR experience with a grass prop, where users can feel virtual sensations and ground props under the sole. This experience is challenging for existing vibration-based tactile interfaces for feet because users cannot avoid feeling the vibrotactile actuators. As an example, we developed a jungle survival simulator. In this experience, users must find a tool to survive barefoot in a jungle. Figure 13 (a) depicts the user walking in the grass prop. While they do not see the virtual twig on the ground, as it is hidden under foliage, they still feel it when stepping on it. They feel it via electrotactile feedback while simultaneously feeling the real grass prop under their feet, as depicted in Figure 13 (b). Finally, they use the virtual twig to obtain an apple from a tree.

Figure 13: Using FeetThrough to feel both virtual sensations from stepping on VR objects as well as real ground props.

6.2 Use-case 2: Posture Feedback for Yoga

Figure 14 illustrates how our device can enhance barefoot activities, such as yoga. Yoga involves maintaining balance in various poses, which can be challenging. In this application, we attached pressure sensors are attached to the corners of the sole, as depicted in Figure 14 (b) When this user leans too much to their right side, (c) the pressure sensor values on the right side will increase; and, in response, (c) electrotactile stimulation will be delivered to the side experiencing higher pressure, alerting users that they are putting too much weight there.

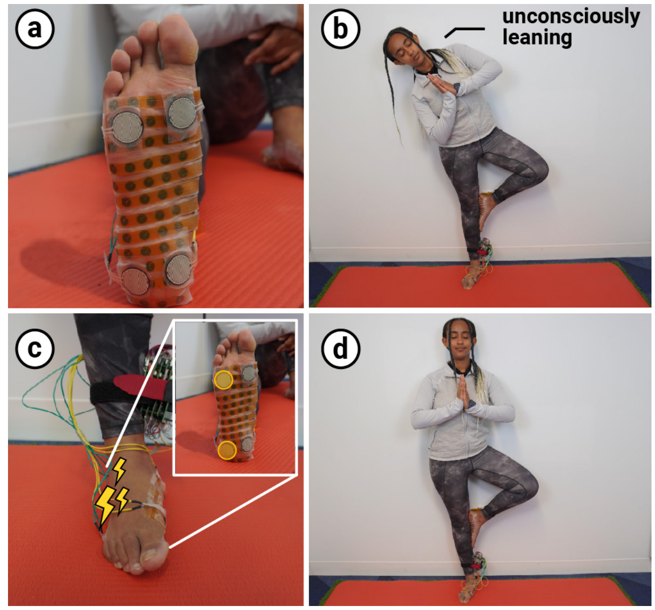

Figure 14: Postural control via electrotactile while barefoot.

6.3 Use-case 3: AR Navigation while Walking

In Figure 15, we demonstrate how our device provides haptic cues that guide users, including perhaps those in low-vision situations, to a room inside of a building while still allowing them to feel physical tactile paving under their feet.

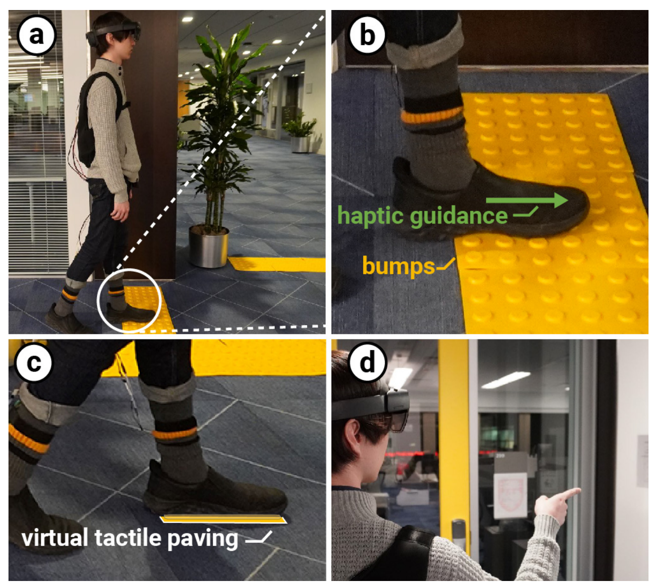

Figure 15: Electrotactile for haptic guidance in real terrains.

These tactile paving surfaces provide haptic information to users with low vision—unfortunately, they are not ubiquitous. Our interface, paired with a HoloLens 2 and a preloaded building map for spatial tracking, allows us to digitally "extend" the concept of tactile paving by rendering the haptic guidance via the electrotactile interface. Figure 15 (a) depicts the user walking over (real) tactile paving. Note that, as depicted in Figure 15 (b), the user is feeling simultaneously the bumps on the tactile paving and a haptic arrow indicating to “continue forward.” However, as depicted in Figure 15 (c), while tactile paving is not ubiquitous in this building, our device extends its reach and continues providing users with tactile sensations even outside the paving, allowing them to find their way.

7 FUTURE WORK & LIMITATIONS

Study limitations. As with any study, ours is not without limitations. While we required participants to stand and step with their full weight on the shapes, we did not require them to walk around or run. The studies were conducted without walking (yet with *active stepping*) to minimize fatigue, enable a focused examination of the discrimination threshold, and measure the interference of haptics with the perception of real objects. To effectively utilize *FeetThrough* in mobile scenarios, such as in use-cases 1 & 3, further investigation on the effects of walking and running (dynamics) is required. We expect that running would decrease the accuracy of both vibrotactile and electrotactile, as stronger ground vibrations need to be accounted for.

Moreover, to keep the duration and difficulty of the task reasonable, we opted for four simple shapes rather than a larger number. However, it is worth noting that shapes were presented simultaneously across two modalities (physical and haptic shapes), resulting in a fairly difficult task. We recommend that researchers take these limitations into account when building upon our results.

Towards everyday use. Our prototypes require manual attachment and individual calibration, which are open challenges in electrode-based devices [36]. Moving towards everyday usage of *FeetThrough*, one can envision electrodes integrated via conductive threads into socks (textile electrodes [29]) and automating the calibration process [30].

8 CONCLUSION

We proposed an electrotactile foot interface designed to enable users to experience not only haptic feedback but *also* the physical terrain under their feet. We identified three advantages of our approach compared to vibrators: (1) users can simultaneously feel physical objects beneath their soles and distinguish between haptic feedback and real-world sensations; (2) electrotactile stimulation has half the discrimination threshold of vibrotactile stimulation, enabling users to better differentiate multiple stimuli than with vibration; and (3) our *FeetThrough* prototype, at 0.1 mm thick, is thinner than vibrators, allowing for barefoot experiences. These benefits were validated through two user studies and illustrated with three additional applications.

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