Designing Interactive Shoes for Tactile Augmented Reality

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ABSTRACT

Augmented Footwear has become an increasingly common research area. However, as this is a comparatively new direction in HCI, researchers and designers are not able to build upon common platforms. We discuss the design space of shoes for augmented tactile reality, focussing on physiological and biomechanical factors as well as technical considerations. We present an open source example implementation from this space, intended as an experimental platform for vibrotactile rendering and tactile AR and provide details on experiences that could be evoked with such a system. Anecdotally, the new prototype provided experiences of material properties like compliance, as well as altered perception of their movements and agency. We intend our work to lower the barrier of entry for new researchers and to support the field of tactile rendering in footwear in general by making it easier to compare results between studies.

CCS CONCEPTS

• **Hardware** → **Haptic devices**; *Sensor applications and deployments*; • **Human-centered computing** → *Mixed / augmented reality*.

KEYWORDS

haptic footwear, vibrotactile augmentation, haptic rendering

ACM Reference Format:
Dennis Wittchen, Valentin Martinez-Missir, Sina Mavali, Nihar Sabnis, Courtney N. Reed, and Paul Strohmeier. 2023. Designing Interactive Shoes for Tactile Augmented Reality. In *Augmented Humans Conference (AHs '23), March 12–14, 2023, Glasgow, United Kingdom.* ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3582700.3582728

AHs '23, March 12–14, 2023, Glasgow, United Kingdom

ACM ISBN 978-1-4503-9984-5/23/03.
https://doi.org/10.1145/3582700.3582728

1 INTRODUCTION

When we think of devices for VR and AR, the first things that to come to mind likely are displays. The next type of hardware we might think of likely are controllers or headphones. However, beyond vision, hearing, and hand movements, there are very few areas where device designs have converged in such a manner. That is not to say that other input and output modalities are not also important. Especially, haptic experiences in VR and AR are something generally considered desirable. There is also a recognition in the importance of our feet in how we engage with the world [60, 74]. Consequently, a small but persistent research area in VR and AR is the design of interactive shoes for tactile augmented reality.

This has led to a wealth of literature featuring novel shoe prototypes. These devices range from vibrotactile augmentation [58, 60, 72], to mechanical approaches [17, 54], all the way to direct electrical interfaces with the body [9]. Recent advances in vibrotactile rendering of tactile experiences such as friction [39, 70], compliance [31], texture [60], torsion [22] and even complex object interactions [82] suggest that vibration can be a much more powerful tool in this context than one might superficially expect. We focus on vibrotactile actuators as they are comparatively easy to integrate in shoes, while providing powerful illusions of material properties and material interaction.

However, unlike with other VR and AR hardware such as displays, controllers or headphones, there are no commercial devices available which might serve as a platform to develop on top of, or act as benchmarks to compare with. This has two negative aspects. It requires researchers to continuously re-invent the wheel, leading multiple different teams (e.g., [60, 65, 74]) to repeat very similar engineering efforts and simultaneously making the research area difficult for new researchers to enter. It also makes it difficult to compare, contrast, or contextualize existing work as a shared frame of reference is missing.

The purpose of this paper is to discuss the design design space of such shoes. We argue that a shared understanding of the design space can act as a shared frame of reference. With this shared understanding many of the implicit design assumptions and decisions can be made explicit. This will help future researchers design their own shoes, and also support contextualizing their work. Additionally, we show by example how this design space might be used in creating a prototype which can create rich tactile experiences. This prototype is open source[1], can easily be reproduced, and lowers the barrier of entry for new researchers to conduct work in this field. We also provide an overview of experiences which can be created by such shoes, based on empirical reports and supplemented by literature. As such, the contributions of this work are a) a discussion of the relevant design space, b) an open-source example implementation and c) reports of experiences that can be created with such a prototype.

2 RELATED WORK

In this section, we discuss the state of the art of research in vibrotactile rendering and augmented footwear. We then highlight augmented footwear systems based on vibrotactile rendering methods before discussing the value of open-source tools for science.

2.1 Vibrotactile Rendering

Carefully designed vibrotactile signals can be used to create experiences of forces and materials exceeding what one might naively believe vibration is capable of. For instance, Romano and Kuchenbecker used prerecorded acceleration of a pen moving over textures to vibrate a handheld device in a way that users experienced these textures on smooth surfaces [51]. In a psychophysical experiment, Strohmeier and Hornbaek found that the timbre and granularity of vibrations can create distinct experiences, while the amplitude alters the perceived strength of a texture [61]. Yao and Hayward rendered vibrotactile cues on a handheld tube to simulate the dynamics of a rolling ball inside the tube [82]. Participants were able to estimate the length of the inner cavity from solely rendered vibrations.

Another approach demonstrated by Kildal was that rendering of vibrotactile feedback based on the user's movement can create an experience of compliance [31]. This vibrotactile rendering approach of vibration coupled with the human motion was further used by Strohmeier et al. to create an experience of changing material composition [59]. Heo et al. generated experiences of bending, stretching and twisting by rendering vibrations based on the changes in force and torque applied by the user [22]. They also generated an experience of compliance by vibrotactile rendering based on the tangential force provided by the user [21]. Sabnis et al. presented an open source vibrotactile rendering system which can be used to implement these experiences [53].

Vibrotactile illusions are another approach to generate high fidelity renderings. One of the earliest known vibrotactile illusions is the apparent tactile motion illusion. Here, two vibrotactile stimuli placed in proximity on the skin with overlapping actuation times would not be perceived as two actuators, but rather as a single actuator moving between them [8]. Israr and Abnousi used this illusion to create calming sensations on the forearm [25]. Alles found that a phantom sensation of a vibrating actuator can be created by providing two vibrotactile stimuli on two different parts of the arm [3]. Tawa et al. proposed mathematical models to extend the range of presentation of the phantom sensations beyond the conventional inter-stimulus model [68]. Israr and Poupyrev proposed an algorithm called *Tactile Brush* to create smooth two-dimensional motions using the apparent tactile motion as well as the phantom sensation [26]. With this algorithm, they were able to design high-density sensations with a few actuators. Rendering asymmetrical vibrotactile stimuli on the skin has been used to successfully provide directional cues and angular velocity cues for certain body movements [5, 52].

Despite all these developments in vibrotactile rendering, the robustness of the rendering is dependent on physiological parameters of the human body as well as the technological constraints. With feet being one of the less sensitive areas to tactile stimuli, vibrotactile rendering for shoes affords its own line of research, which we aim to support with this paper.

2.2 Augmented Footwear

Foot interfaces have a tradition in Human-Computer Interaction research and evolved from stationary platforms over wearables to highly integrated devices for human augmentation [12]. Furthermore, augmented footwear is still gaining attention in research. Although many different approaches have been developed and studied in the last two decades, referring to Elvitigala et al. there are still open challenges, especially to create interfaces that sense biomechanical parameters and to provide subtle and efficient feedback [12]. Even though there are efforts for open-source devices [50], Elvitigala et al. described the lack of widely available augmented footwear as one of the open challenges as well [12]. This is the challenge we wish to address in this paper.

In their review of more than 100 academic papers, Elvitigala et al. identified categories of popular applications for augmented footwear like sports and well-being, rehabilitation, assistive devices, or VR [12]. In sports and fitness instrumented shoes and insoles support users to learn motor skills, for example to improve their climbing technique [15], maintaining the correct posture during exercises [13, 14], or to support online fitness sessions [67]. Symbolic and metaphoric vibrotactile patterns have been implemented with multi-actuator devices (e.g., 4×4 matrix [75]) to indicate directions in navigation tasks [66, 75]) as well as systems to guide users by inducing a certain walk cycle [80] or using tactile illusions [36]. Integrated [2, 20] and distributed systems [81] have been used in the domain of rehabilitation for gait training (e.g., post-stroke rehabilitation). Other assistive applications are for instance supporting deaf dancers perceiving the rhythm and tempo of music [83] or to elicit cognitive awareness of people with Alzheimer's disease, specifically avoiding mental trance [46]. Finally, a large corpus of work can be found in the domain of VR and AR, which we focus on in the paper.

There is a broad range of approaches used for augmenting walking for VR and AR. These include *grounded systems* which can be

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[1] https://github.com/sensint/Haptic_Shoe

quite powerful, enabling experiences such as falling [55], or stepping up staircases [54]. A popular and somewhat more light-weight approach are pneumatic systems. Here, air-filled bladders are used to render an object or terrain [77–79]. *Non grounded systems* have also been explored, for example, by using the air flow of multiple fans attached to the calf to simulate resistant force while walking in fluids in VR [29]. Another interesting approach includes shoes with *variable friction* soles, which can mediate the shoe-floor contact [24, 39, 70].

Generally speaking, the above examples come with significant mechanical complexity, cost, or weight. Due to the relative ease with which vibrotactile actuators can be integrated in everyday shoes, their comparatively low energy requirements and minimal requirements for additional moving parts, they are the most commonly seen approach in such augmented footwear [12]. As vibrotactile feedback is also capable of creating a rich breadth of sensations, and because we intend to design shoes which are as easy to reproduce as possible, we also think vibrotactile actuation to be the preferable approach of augmenting footwear for VR and AR. In the next section, we present work which applies vibrotactile rendering methods to augmented footwear.

2.3 Tactile Rendering in Shoes

There is an active research effort on applying the findings from vibrotactile rendering research and vibrotactile illusions to augmented footwear. Early approaches used audio-haptic systems based on audio recordings to simulate the experience of walking on different grounds [47, 58, 73]. These prototypes typically used sensors for detecting impact and then playing back predetermined audio-based vibrotactile or acoustic signals. Turchet furthermore proposed several physically inspired models for foot-floor interactions in combination with anthropometric features and parameters of different shoe types to synthesize a broad range of realistic footstep sounds [71]. These sounds were also rendered as vibrotactile feedback.

Other work directly implemented illusions that have already been applied to other HCI areas to interactive shoes. For example, Strohmeier et al. demonstrated measuring the pressure dynamics of the foot, and generating corresponding vibrotactile signals in real time [60]. This was used to create compliance experiences inspired by Kildal [31] which were in turn used to create experiences such as stepping on to foam or gravel [60]. Another interesting use of vibrotactile illusions was presented by Lee et al. [34]. They augmented the foot with two actuators–one on the sole and the other on the instep of the foot–to evoke a body-penetrating phantom sensation [34], similar to prior non-wearable work using apparent tactile motion and phantom sensations [26, 57]. An interesting side note is that while the bulk of these prototypes were designed with the intention of augmenting the experience of the ground, they might also augment the experience of the body. For example, Tajadura-Jimenez et al. demonstrated a system that could change the perceived weight of users through manipulating the sound of their footsteps [65].

Currently, most prototypes are not capable of adapting their feedback to foot dynamics in real time [58, 73], or are restricted to foot dynamics at a specific location [60] , or purely focus on input, without any actuation [50]. One of the goals of the device we present in this paper is to support exploration of a system which is responsive to foot-dynamics in multiple dimensions.

2.4 Open Source Tools in Science

Reproducibility is one of the foundational pillars of modern science. To encourage transparency of the research and open source sharing of resources, data, research methodologies, successes and failures, etc., the Open Science movement has gained a lot of importance in recent years [1]. Current practices in the field of vibrotactile haptics rely on re-inventing and re-development of devices used for research [56], which restricts the bandwidth available to researchers to expand the boundaries of knowledge. This could be prevented by creating scientific tools and platforms that are free and open source [48]. Such open-source hardware does not only provide better science, as results are easier to reproduce, these open-source tools are also cheaper, making them accessible also to institutions with less available funding [69].

Open-source microcontroller platforms such as Arduino or Teensy have had a substantial impact on supporting such open-source scientific hardware [10]. For instance, Reinhardt et al. published material for researchers to build open-source shoes for VR applications [50]. However, the accessibility and scalability of augmented footwear is still an open challenge [12]. In our work, along with demonstrating the prototype development process, we make all the designs, software, findings and lessons learned openly available. Thereby, we both support easy replication of our own experimental platform, while also sharing what we learned on the way to encouraging others to build remix and adapt the existing design to their own needs and to create even more versatile shoe augmentations in the future.

3 DESIGN DIMENSIONS

When building vibrotactile shoe prototypes, the literature typically reports a subset of the design choices made by researchers. What is often omitted is the broader design space these choices are sampled from; what other options could have been chosen. Here, we wish to discuss this broader space, both to help contextualize choices other researchers already made and to guide researchers interested in creating their own custom vibrotactile shoe prototypes.

3.1 Actuator Selection

Vibrotactile actuation can be provided with different technologies. In this section, we discuss the properties of some widely used actuators as well as scientific considerations.

3.1.1 Actuator Properties. Vibrotactile feedback is provided primarily using Linear Resonant Actuators (LRAs), Eccentric Rotating Masses (ERMs) and piezoelectric actuators. Important factors in choosing an actuator include **independent control of frequency and amplitude**, as well as overall **acceleration**. This is why LRAs are the most common actuator found in research on vibrotactile rendering (e.g., in [45, 51, 60, 61, 72]). See Figure 1 for an overview of some actuators we like.

Other parameters which are important to consider include **time to signal onset**, or the lag between the electrical signal and the mechanical output. Here there is often a trade-off with velocity.

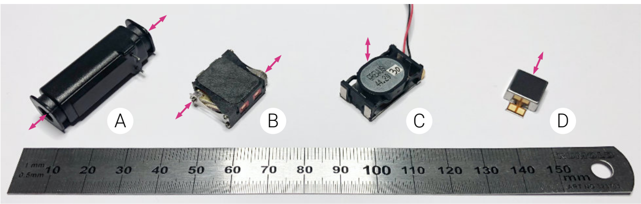


Figure 1: Vibrotactile Actuators for providing high-definition tactile feedback: (A) Arctronica HapCoilOne (Haptuator Mark II-D), (B) Lofelt L5, (C) Grewus EXS 241408W A, (D) Vibronics VLV101040A. The direction of the vibration is indicated by arrows.

For example, the HapCoilOne by Actronica requires only 14 ms to full amplitude, with an acceleration of 11.4 g (at 0.1 kg, peak-to-peak). While the HapCoilPlus by Actronika requires 29 ms, but can then reach a peak acceleration of 19.3 g. Depending on application, the **bandwidth** is also important. Broadband actuators such as the HapCoilOne or Apple's Tactile Engines are able to provide strong signals at a broad range of frequencies, enabling detailed texture rendering [51, 61]. Other actuators (e.g., C and D in Figure 1) only output their full velocity at specific frequencies, usually tuned around the frequencies we are most perceptive to (approx. 170 to 230 Hz [76]). This is sufficient for many rendering applications, such as generic compliance illusions [31]. Available actuators also differ in terms of **form factor** and **encapsulation**. Some have the moving parts encapsulated (e.g., A and D in Figure 1) and others have them exposed (e.g., B and C in Figure 1). On the one hand, the encapsulation makes an actuator slightly bigger, which could be a limitation for integration in small objects or prototypes with less space. On the other hand, an encapsulated actuator can simplify the integration, for instance placing them in tightly fitting molds without worrying about the exposed moving parts.

3.1.2 Scientific Considerations. A factor not often discussed in actuator choice is the **information availability**. For example, actuators by Actronika are well documented and are built on a legacy of the de-facto standard in vibrotactile rendering so far (e.g.: [40, 51, 58, 60]). This means that experiments using these devices can be easily contextualized with one another, and its behavior can be referenced to datasheets. In contrast, devices such as the Taptic Engine by Apple have been used with much success in prototypes, but as their documentation is not readily available and, because they do not have the same tradition as the Actronika devices, experimental results obtained using them are more difficult to put in context with the larger body of research. Finally, for building research prototypes, **reproducibility** is essential. Here, opting for low-cost devices is a simple way of ensuring a device is easy to replicate. For example, while reproducing a prototype using 5-6 Actronika Actuators will easily cost more than 1000 €, the same device using Vibroncis actuators can be likely built for under 50 €. However, cost is not the only thing to consider in this context. As the haptics industry is currently developing at a rapid pace, product life-cycles can be very short. For example, start-ups might be bought up by larger companies, without the guarantee that their products will continue to be available. This, for example, is presumably the reason why the excellent Lofelt actuator is no longer available.

In summary, selection of the correct actuator for a research prototype is a complex question. It is not sufficient for researchers to consider the electrical and mechanical specifications of the actuators in question, instead it is already at this early stage that questions around experimental validity and reproduceability must be considered. Researchers must not only consider the actuator itself, but also the actuators ecology and economic context.

3.2 Actuator Integration

In this section, we discuss the challenges to integrate actuators in wearable prototypes based on physiological and mechanical constraints.

3.2.1 Physiological Considerations. The perception of vibration differs depending its frequency [76] and on the body part where it is provided at [11]. Mechanoreceptors in the glabrous skin which are receptive for vibrations are the fast adopting (FA) Meissner corpuscles (FAI) and Pacinian corpuscles (FAII) [27]. In this work we focus on the FAI and FAII receptors because these are sensitive to the frequencies which typical vibrotactile actuators can provide, i.e. FAI: 5–40 Hz and FAII: 100–300 Hz [30]. Their distribution across the plantar sole as well as the size of the receptive fields have been investigated among other properties in several studies [62–64]. Findings indicate that if working with lower frequency actuation, one might use a comparatively dense array of actuators, as the smaller receptive fields of Meissner corpuscles are indicative of better spacial discrimination (Figure 2 A). For higher frequencies, however, the larger receptive fields of Pacinian cells suggest that dense arrays are not beneficial, as the size of the perceptive fields indicate lower spatial discrimination (Figure 2 B). Additionally, one should also consider that vibration travels through the skin, so even receptive fields that are not adjacent to the point of stimulation might still respond to it.

A crucial factor for placement and density of the actuators is the two-point discrimination threshold (Figure 2 C). At a frequency of 200 Hz this distance ranges from approximately 1.5 cm at the big toe to 3.4 cm at the heel [33]. In the arch region, the thresholds slightly increases from the lateral (2.61 cm) to the medial arch (2.99 cm), whereas the threshold is almost constant at metatarsal area (2.1 cm) [33]. If the discrimination of certain actuators is crucial for the intended augmentation, one should not exceed these area-depended distances, though the physiological measures of receptive fields we discuss suggest that lower frequency devices might achieve a higher spatial discrimination.

The actuator placement might also depend on the types of interactions that should be augmented. For instance, augmenting the weight shifting in a balancing task would need actuation in the longitudinal and lateral direction independently. Therefore, at least two actuators are needed per axis, but the number can be increased depending on the desired spatial fidelity. Depending on the form factor of the actuator, placing them between the metatarsal and arch area might be challenging. While walking, the extension of the toes right before the toe-off causes a deformation (bending) of the shoe sole and hence could dampen the vibration or even damage the actuator. Large actuators should therefore not be placed in this area.

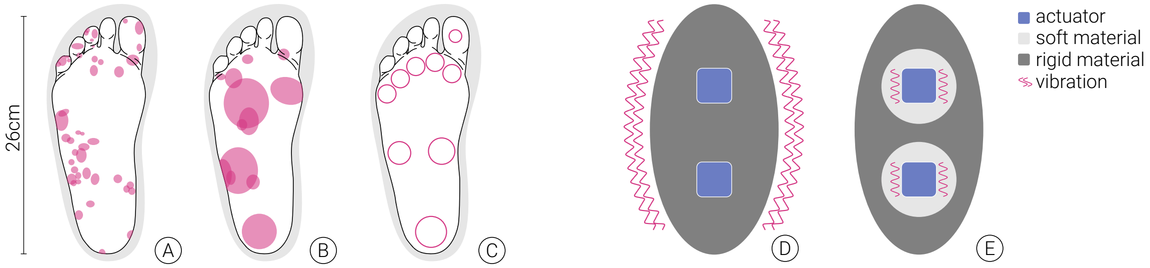


Figure 2: Receptive fields of individual instances of fast adapting mechanoreceptors (A) Meissner corpuscles (FAI) and (B) Pacinian corpuscles (after Strzalkowski et al. [63]). (C) Two-point discrimination thresholds at 200 Hz stimuli (after Kowalzik et al. [33]). Illustration of multiple actuators attached to a (D) rigid material to vibrate the entire object, and (E) embedded in a soft material to provide solely localized vibrations.

Placing actuators on the top or at the side of the foot instead could be an alternative, depending on the form factor of the footwear. Experiments demonstrated that providing vibrotactile stimuli on the instep of the foot can also evoke illusory tactile sensations on the foot sole [23, 34].

3.2.2 Mechanical Integration. We divide the vibrotactile actuation in footwear into two main approaches: vibrating the entire shoe, and actuating specific areas of the shoe (Figure 2 D and E respectively). For the latter, a key challenge is the propagation of the vibrations in the entire shoe. To vibrate specific areas in physiologically relevant regions while walking, it is important to localize the vibrations to those particular regions. A soft material which dampens the vibrations more than a rigid material can be used to encapsulate the actuator such that the maximum vibrational energy is transferred in the desired (vertical) direction. For instance, inlays made from silicone can encapsulate the actuator to serve two primary purposes: 1) **decouple vibration from the soles** which limits the energy dissipation in multiple directions, thus focusing the vibration to a pre-defined target area (illustrated in Figure 2 E), and 2) **prevent grounding of the actuator** if the pressure on the actuator is exceeded and thus the vibrotactile rendering is not perceivable anymore. Moreover, such a targeted vibration can create realistic effects like stepping on a pebble or having successive actuation from the heel strike to toe-off phases of the gait cycle.

3.3 Sensing

Sensing of interactions and movements in the shoe provides crucial information, for instance, regarding the different phases of the foot movement during a gait cycle. However, sensing these interactions and movements is challenging, since the sensing setup must not interfere with the natural gait cycle of the user and needs to fit inside the footwear.

3.3.1 Technologies. Several sensing technologies have been successfully used in various applications, and smart insoles became popular and affordable in the last decade [4]. Pressure sensing and motion sensing are the two main types of sensing required for applications ranging from balancing tasks and sports movements to gait analysis in rehabilitation, as well as healthy adults [12]. For sensing pressure, various approaches have been implemented in research. Martini et al. used opto-electronic sensing, in which a silicone layer deforms based on the applied load, thus closing the light path between the emitter and the receiver which causes a change in the output voltage [37]. On the other hand, capacitive sensing is one of the recently used techniques [7, 35], in which a capacitive sensor consisting of two conductive plates is separated by a dielectric material. Based on the load applied, the distance between the conductive plates is modified, thus generating a variation in capacitance. Although opto-electronic and capacitive sensors provide increased accuracy, due to comparatively high latency, expensive setup and durability concerns, Force Sensitive Resistors (FSRs) are a suitable and affordable alternative and are widely used in research (e.g., in[18, 47, 58, 60]).

Pressure sensors can be used to retrieve information about the motion properties during the stance phases or to identify implicit interactions like the surface type a user is walking on [38]. As soon as the foot is lifted or rotates, one need to use different sensor

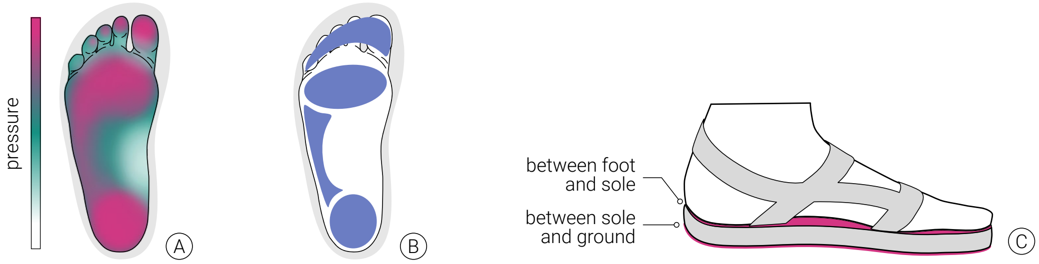
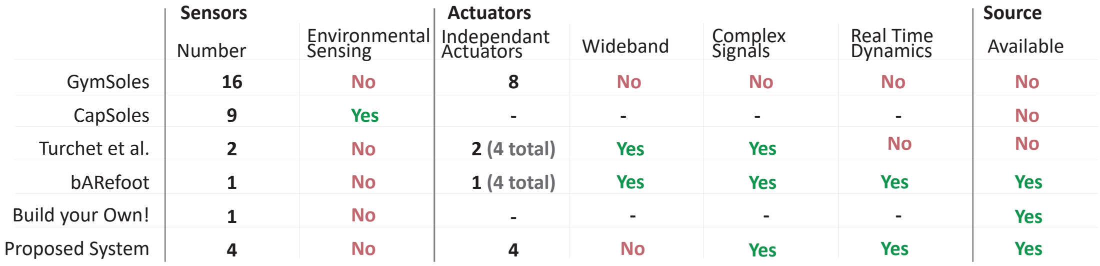


Figure 3: (A) shows the plantar pressure distribution. (B) highlights four uncorrelated regions while walking that are useful to sense pressure dynamics for gait analysis [28]. (C) illustrates two types of interactions that can be sensed with pressure sensors.

Table 1: Comparison of features of selected augmented shoes. GymSoles [14] has more input and output options than others, but low signal resolution, CapSoles [38] and the open source "Build your Own" [50] are purely input devices. The prototypes by Turchet et al. [43, 72] are unable to respond to real time signal dynamics. bARefoot [60] only uses a single sensor/actuator paring.



	Sensors		**Actuators**				**Source**
	Number	Environmental Sensing	Independant Actuators	Wideband	Complex Signals	Real Time Dynamics	Available
GymSoles	**16**	**No**	**8**	**No**	**No**	**No**	**No**
CapSoles	**9**	**Yes**	-	-	-	-	**No**
Turchet et al.	**2**	**No**	**2** (4 total)	**Yes**	**Yes**	**No**	**No**
bARefoot	**1**	**No**	**1** (4 total)	**Yes**	**Yes**	**Yes**	**Yes**
Build your Own!	**1**	**No**	-	-	-	-	**Yes**
Proposed System	**4**	**No**	**4**	**No**	**Yes**	**Yes**	**Yes**

technologies to retrieve these types of information. A common type of sensor for such purposes are Inertial Measurement Units (IMUs). IMUs combine a set of sensors, usually gyroscope, accelerometer, and magnetometer and fuse the data streams to calculate linear accelerations and orientation. These sensors are available as small breakout boards that allow the integration inside the shoe, e.g., in the insole.

3.3.2 Physiological Properties and Positioning. An important decision for an augmented footwear is the number, locations, and the size of the pressure sensors. This is mostly determined by the physiology of the foot (i.e., pressure distribution) and the type of activity that needs to be analyzed. Figure 3 A) illustrates a typical pressure distribution for gait. Kanitthika and Soo Chan investigated the distribution of the plantar pressure while walking. Their goal was to find a minimal set of optimal sensor positions on the foot by identifying regions where the pressure dynamics were minimally correlated with other foot areas [28]. Based on an insole equipped with 99 sensing elements (Pedar-X system by Novel) they identified four regions: 1) the heel, 2) the outline of the arch, 3) the metatarsal, and 4) the toes [28] (illustrated in Figure 3 B). In a typical gait cycle each (or a set) of these areas can be related to a specific phase, for instance, a rapid peak at the heel indicates a heel-strike whereas a rapidly reduced pressure at the toe indicate the toe-off (i.e., beginning of the swing phase of the corresponding leg).

However, the number of sensors depends on the intended application. While simple trigger (e.g., for foot tapping) only require a single sensor, two to four sensors are suitable to investigate gait patterns, but other interactions might need more sensors. For instance, to sense the dynamics of foot movements during a balancing task each area would need at least two sensors in the longitudinal as well as the lateral direction.

When using pressure sensors to investigate the users' movements and interaction, it is also worth thinking about the type of interaction that should be sensed. This could be the pressure dynamics between the shoe sole and the ground or the pressure dynamics between the foot and the insole (Figure 3 C). These measures are highly correlated, but different from each other. The small discrepancies are particularly important for rendering material experiences, where using pressure dynamics between the shoe sole and ground for generating the augmentation might be perceived as if the properties of the ground change, while the pressure dynamics between the foot and insole might be perceived as an augmentation of the shoe itself.

3.4 Construction

One might have a bespoke shoe handcrafted by an expert shoemaker according to our specifications. Alternatively, one might build upon some of the impressive generative work available in the design and HCI literature (e.g., [6, 16, 41, 42, 84]). Here, again, there is no clear best solution, as different approaches have their own benefits and drawbacks.

A professionally handcrafted shoe would be an optimal solution in terms of comfort, the robustness related to the chosen materials and fabrication techniques, as well as the customized integration of the electronics. However, this specialized knowledge and skills would reduce the reproducibility. The parametric and generative 3D design approach addresses this, for example with algorithms that generate shoe soles considering different physiological properties (e.g., foot shapes or sizes) for 3D printing [6]. Even though this simplifies the reproducibility and offers opportunities towards customization and personalization of the designs [42, 84], the integration of electronics is not part of such systems and hence needs additional effort. Hence, one might consider reducing the complexity by only using rather simple CAD software to design a shoe (or shoe sole) for a naïve 3D printed approach (e.g., with flexible filament like TPE or TPU). While this would allow many researchers to replicate the devices easily, the prototypes might lack comfort or are not as robust to last for longer than a couple of studies.

4 EXAMPLE IMPLEMENTATION

In this section we demonstrate how the above considerations, in conjunction with real world constraints and requirements, lead to concrete design choices. In this case, we set out to create a prototype to be used in the exploration of tactile renderings. Moreover, our goal was to create a device which is easy to create, so any experiment run with it can be replicated, and which is sturdy enough to withstand the trials of an experimental session.

4.1 Prototype Constraints

4.1.1 Application Constraints. In this work, we focused on tactile rendering to augment the human experiences of walking on different surfaces and textures as well as the body perception while balancing. Therefore, an augmented footwear needs to sense the dynamics of the human motion (i.e., progression of the pressure distribution on the plantar region) and create the vibrotactile feedback accordingly. While the perception of textures could be realized by augmenting the entire foot sole at once [60], the augmentation of shifting the center of pressure (COP) during a balancing task should be localized depending on the current COP and the direction of change [13, 14]. Since we aimed to augment a variety of activities, we decided to incorporate multiple sensors and actuators to enable such localized vibrotactile renderings. We decided to use the four sensing regions discussed in Section 3.3.2. Moreover, we chose the same positions for the actuators to spatially couple the sensing and actuation for localized augmentations.

4.1.2 Construction Constraints. We focused on simple techniques for the design and construction, i.e. semi-parametric CAD modeling and fused deposition modeling (FDM) 3D printing. Decisions were made due to available materials, machines and tools in the lab as well as the authors' knowledge and skills (e.g., CAD modeling, silicone molding, 3D printing, laser cutting, PCB design). We aimed to construct sandals that are suitable for slightly different shoe sizes. Since none of the authors had skills in traditional shoe manufacturing, we for example relied on retail sandals for the strap system to reduce the efforts to get a certain level of comfort for the wearer. Additionally, we aimed for robustness of the 3D printed soles, so they can withstand bending or scratching over rough materials.

4.1.3 Scientific Constraints. In scientific contexts, it is important to enable other researchers to reproduce the apparatus and recreate studies to prove or falsify the results or to build upon previous work. Even parameters that are given on datasheets need to be contextualized in the actual prototype to understand their effects in the entire system (e.g., the frequency response curve of an actuator). Hence, it needs detailed information on the construction as well. This also applies to the fabrication methods, materials, and tools. In terms of tools, the accessibility in other labs could be a limiting factor. We therefore suggest to use widely available and affordable tools (e.g., FDM printers), and if possible to prefer simple fabrication methods over complex ones which would need special skills or tool chains.

4.2 Construction

Based on the highlighted constraints, we designed and build a pair of sandals. In particular with regards to actuator capabilities and sensor numbers, we were unable to use existing available designs (See also Table 1). The soles were designed in a semi-parametric manner in a CAD modelling software (Fusion 360 by Autodesk) and 3D-printed, whereas the straps were taken from retail sandals (C and D in Figure 4) to further simplify the construction and to provide a certain level of comfort. To encapsulate the sensors and actuators, we designed a bottom and top layer, that are glued together in the final assembly (Figure 4). All 3D models were sliced with 20% infill of a Gyroid pattern using the Cura Slicer (Ultimaker) and printed with a flexible Thermoplastic Elastomer (TPE) filament (TPE95A by Jabil) on an Ultimaker S5. This infill pattern was chosen to reduce the weight of the 3D-printed parts. The overall weight of a single, fully assembled sandal (incl. electronics) was approx. 300 g. The weight of 3D-printed parts per sandal were 134 g (top: 86 g, bottom: 48 g).

Figure 4: The first iteration of the augmented footwear: (A) Positioning of the sensors and actuators; (B) The bottom and top part of a sandal with four FSR sensors (left) and four actuators (right) embedded into the sole with silicone inlays; (C) The top part with off-the-shelf straps (left) and the profile of the bottom part (right); (D) The fully assembled sandal.

Four FSR sensors were integrated in the bottom layer and four actuators were integrated in the top layer. The cables were routed in pre-defined grooves. Figure 4 A) illustrates the positions of the components and how sensors and actuators are stacked. To focus the vibration to a targeted area and to prevent the vibration grounding, we cast silicone inlays (MoldStar 20T, Shore 20A) for the actuators. We opted against wide-band actuators as we did not require them for our desired application, and so we can use smaller actuators. The straps were fixed with hot-glue inside pre-defined slotted holes.

4.3 Electronics and Software

The sandals with the integrated sensors and actuators are connected to a custom PCB that holds all the electronics to communicate with the control software and to provide the vibrotactile augmentation. Figure 5 presents on the left all components, as well as the technologies and protocols used for communication (i.e., transfer of control signals and data).

4.3.1 Electronics. The embedded system design is based on the open-source Haptic Servo by Sabnis et al. [53]. Haptic Servos are

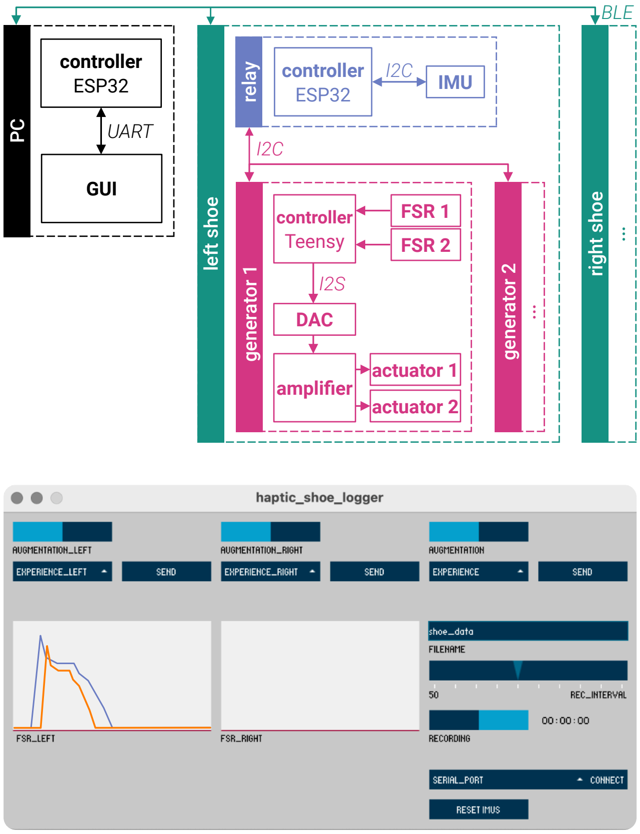


Figure 5: Top: Schematic illustration of system components and the communication protocols. Bottom: GUI software to control the augmentation and record sensor data streamed from the augmented footwear.

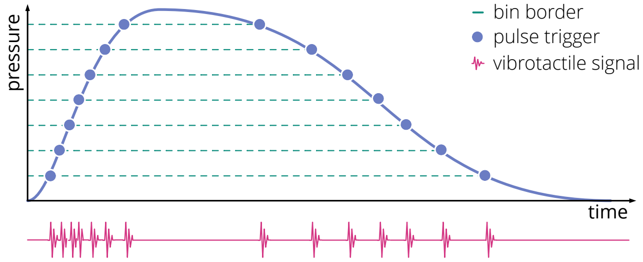


Figure 6: Illustration of the tactile rendering approach. Impulses are played back at a frequency proportional to how fast the pressure changes. As a result vibration is experienced as caused by the interaction between the user and the suface they are stepping on.

embedded devices which contain an analog input for measuring human action dynamics, a microcontroller for creating a control signal based on these sensor readings, a digital to analog converter to output this signal, and an amplifier for driving haptic actuators. This enables fast prototyping of haptic rendering systems [53].

In the case at hand, the Haptic Servo system was implemented using Teensy 4.0s and modified to drive two actuators simultaneously. Each sandal was connected to two of these Teensy 4.0s (Figure 5 left). Each Teensy reads two analog signals from FSR sensors (FSR06BE by Ohmite) and generates two independent output signals (i2s), respectively. The Teensy's audio output channels are fed into a 16 bit DAC (PT8211 Audio Kit) and the line level audio is amplified by a 3.7 W class D stereo amplifier (Adafruit MAX98306). Because of their small footprint, we used the VLV101040A wideband LRAs by Vibronics to turn the amplified audio signal into vibrations.

The signal generators (Teensys) are connected to an ESP32 (M5Stack M5Stamp Pico) that acts as a communication relay (bidirectional via I2C). The relay-controller receives and transfers control commands to the signal generators and receives sensor data (FSR) from the signal generators and forwards them to the control software (subsubsection 4.3.3). Additionally, the ESP32 has an IMU (BNO055) attached to retrieve the orientation and acceleration of the sandal. This information is synchronized with the FSR data and sent to the control software via Bluetooth Low Energy (BLE 4.2). The wireless communication allows the system to be freely used within a radius of approx. 10 m (distance to PC).

Another ESP32 is connected via USB to the PC and acts as a BLE transceiver. It receives control commands from the GUI software via UART and forwards the commands via BLE to the sandals' relay controllers. With this additional controller, it is possible to use the system with a computer that doesn't support Bluetooth.

4.3.2 Firmware. The system involves three different firmware: 1) the signal generators running on Teensy 4.0 as well as 2) and 3) the two communication relays running on ESP32, where 2) is also used to synchronize FSR sensor data with readings from an IMU. Each signal generator serves four major tasks: 1) monitors two analog pins connected with the FSR sensors, 2) generate vibrotactile pulses using the stereo audio capabilities of the Teensy Audio Library based on the sensor readings, 3) process control commands from the control software, and 4) send the sensor data to the control software. The augmentation we use in the work is inspired by a method developed by Kildal to make a rigid object being perceived as compliant [31]. The 10 bit value range of the analog readings is divided into a given number of regions (bins). Each bin is defined by an upper and lower bound and is associated with a set of vibration parameters (e.g. duration, amplitude, frequency). If the sensor value crosses a bin border, a pulse with the defined set of parameters will be generated as an audio signal and played back as a vibration (Figure 6). Hence, the dynamics of the vibrotactile feedback unfolds in sync with the dynamics of the pressure applied on the FSR while walking. The definitions of bin borders, associated parameter set, as well as the set themselves are provided as header files in the firmware code. At runtime, the user can switch between different augmentations using the control software.

The firmware for the two communication relays is fairly simple. These implement a BLE central and peripheral respectively to transmit control signals (e.g., start/stop/select augmentation) and to stream sensor data wirelessly. While the controller that is connected to the computer uses a serial connection (UART) to communicate with the control software, the relay controllers at the sandals use a I2C communication to send commands to the signal generators and to retrieve sensor data from them. This controller retrieves orientation and acceleration data from an IMU via I2C.

4.3.3 Control Software. The augmented footwear is connected to a GUI software (Figure 5 right). This software is used to control the augmentation and to record sensor data (i.e., FSR and IMU). At runtime, the user can toggle on or off the augmentation for each sandal separately or for both at once, and can select the type of augmentation itself. A second purpose of this tool is to record sensor data sent from the sandals that can be used for motion analysis later. Users can select a directory and name, as well as a sampling speed before starting to record data. Time-profiles of the FSR data will be visualized while recording. To ensure cross-platform compatibility, we developed the tool in Processing (version 4.0b1). The source code is available in the project's repository[2].

5 EXPERIENCES

To better convey the opportunities of our prototype, we present initial anecdotal experiences. We expect these observations to act as a foundation for future experimental work. We do not claim that they can be systematically reproduced. We share them here to highlight the opportunities of this type of augmented footwear for VR and AR, as inspiration for future directions to explore, and to highlight how choices within the design space might influence the experiences a haptic shoe can convey.

5.1 Setup and Tasks

We tested our prototype on a variety of surfaces for about an hour using two vibrotactile rendering types while walking on these surfaces or balancing on objects (Figure 7). The first rendering type provided a continuous playing vibration as soon as the pressure exceeds a certain threshold, i.e. while standing or shifting the weight. The inverted case, i.e. while lifting the foot, was also tested. The second type of tactile rendering used motion-coupled vibrotactile pulses as described in Section 4.3.2. Here, we used two settings: one with pulses of 11.74 ms (2 cycles), while the second used 50 ms pulses. All vibrations were produced by a sinusoidal signal at 170 Hz (resonance frequency of the actuator).

We also worked with two naive users, Ata and Rishabh (both male, aged 31 and 28, respectively) from different research groups at our institution to test the augmented footwear. The users were naive in the sense that they were not familiar with the design and research goals. These users wore the prototype in a series of tasks which involved weight shifting and lifting the feet in place and walking on different surface textures (in total approx. 40 minutes per user). Both users experienced two motion-coupled vibrotactile renderings, as in our tests among the authors. The main goals of the tasks were to examine the quality of the feedback delivered by the multiple sensor-actuator placement in the implementation and the experience of the compliance illusion as felt in different walking and standing behaviors.

Figure 8 depicts the tasks (T) completed, in the following order: 1) standing and shifting the center of weight while in a confined space, without lifting the feet, 2) walking in a marked rectangular outline, with 90 degree pivots, 3) walking in a marked figure-eight outline, with smoother curved pivots, 4) walking indoors, back and forth between tiled and carpeted flooring, 5) walking up and down a flight of stairs, and 6) walking outdoors, back and forth between grass and mulched wood chips. T1 provided an introduction to the feedback while standing and shifting weight, T2 and T3 different weight shifts and foot contact with the ground while walking/pivoting, T5 lifting the feet individually and climbing, and T4 and T6 contrasts between different surface textures.

Figure 7: In preliminary tests, the authors explored the experience of walking with the augmented sandals on different surfaces, i.e. (1) walking up and down stairs (stone), (2) asphalt, (3) wood chips, (4) grass, (5) tree trunk, and (6) balancing on a springy plate.

5.2 Key Experiences

5.2.1 Compliance. The augmentation provided sensations of compliance for both Ata and Rishabh. While shifting his center of weight, Rishabh described this compliance as like "bubble wrap," something "triggering" with his movement. The compliance was particularly notable in the users' experience of textures underfoot when walking indoors and outdoors, and in applying more pressure in the step when shifting weight and climbing stairs.

The softer textures of the carpet and mulched wood chips were accentuated by the augmentation, creating an experience that the materials were much softer with the vibrations. Rishabh described these materials similarly, with the carpet being "damp" and the mulch "wet": "Walking on the cushion [carpet] makes it softer... I notice the difference. The vibrations are pretty damp... Right now [on the mulch] it feels like walking on a moist surface. Not very hard... when I'm doing this I can feel it's not so soft down there, but when I move it, it is kind of soft, at least softer than there [on the grass]". These softer sensations in turn impacted the perception of the grass as being "harder definitely" and more uniform, although Rishabh recognized that the grass, like the mulch, was not a flat area: "I can feel it is harder than that [the mulch] but then it's also not a plane area, so I doubt it."

The compliance illusion also created an augmented "pressing" sensation when climbing the stairs. Ata felt "the vibration is a bit

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[2] https://github.com/sensint/Haptic_Shoe

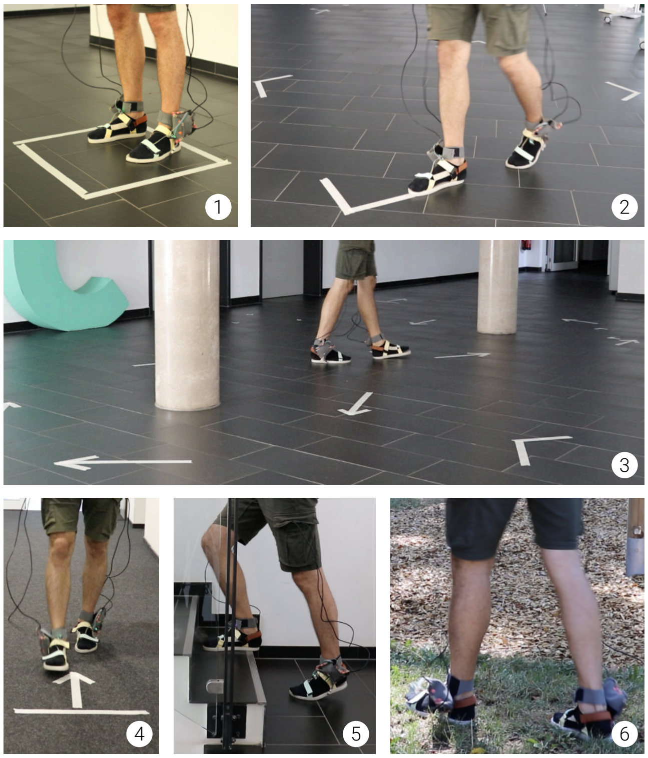

Figure 8: Exploring vibrotactile augmentation indoors and outdoors: (1) exploring the augmentation while standing and shifting the center of mass in a small area, (2) walking along a 3 by 3 meter square, (3) walking an eight-shape between two piles, (4) walking a hallway on two different surfaces (stone and carpet), (5) walking up and down stairs, and (6) walking outside on grass and wood chips.

stronger here with more pressing horizontal than vertical" across his foot. It feels more like a pressing sensation." Rishabh described that "While going down, it does not feel much, but while going up it does vibrate... it feels that the surface is softer. In fact, while coming down I don't feel the vibrations at all... Because I'm going down, I am shifting weight on my toes, and that's why."

5.2.2 Sensor-Actuator Positions. The position of the sensor-actuator pairs across the sole created experiences of differences across the foot and awareness of weight distribution for Ata. While standing still and shifting his center of weight, Ata commented that "As I am leaning on one direction, I'm feeling more vibrations happening on that direction on both feet." He also described how the vibrations at the tip of his foot were the most able to be sensed. While walking along the marked shapes, the shifting of the weight through the step were most notable when walking slowly: "I can sense the pivoting slowly like shifting my weight from that side to this side." With the sharp corners of the rectangular shape, "I feel the front side and the central sites of the foot vibrate more than the back and the outer side."

5.2.3 Discomfort. While using the inverted continuous vibration (feedback applied to lack of pressure), the prototype was able to deliver a feeling of being uncomfortable to move. Because the vibration is constant while no pressure is applied to the sole, Nihar experienced feeling not wanting to move and needing to stand still with full weight on both feet in order to not receive the constant feedback. In contrast, when the continuous vibration based feedback was applied on press (e.g., while standing) Nihar preferred to keep on walking to avoid the continuous feedback.

5.2.4 Returning to Reality. Another notable experience described by Ata came after the vibration was turned off. Ata commented during walking along the figure-eight shape that he was "much more aware of my state of walking... it seems very natural." After the tasks were completed and the feedback was turned off, Ata remarked that his walking "Feels heavy... It does feel weird because I think the nicest feeling was [being] aware of your walking." This experience is particularly interesting, as it indicates the potential for designing dedicated experiences for this transition phase, as investigated by Knibbe et al. for VR scenarios [32]. Furthermore, Ata described the feedback from the shoe as providing a kind of extension for what the foot naturally feels but is normally masked by a shoe: "It's like walking in the dark and not understanding what you're stepping on. When you close your eyes, you get more sensations of feedback [because] we need to focus on it. You already get that feedback. I really like that feature [about the haptic shoe]. I feel like it was like walking on sand barefoot. It feels like your shoes cause you to not have those sensations normally, but when you wear this it helps you to have a sensation of your walking cycle."

6 DISCUSSION

6.1 Reflections on the Implementation

Generally speaking, the sandals performed as expected. We demonstrate that a relatively simple and low-cost implementation is able to create experiences such as compliance, material textures, weight shifts, motivation to move or not move, and a heightened awareness of walking and their tactile surroundings, which people missed once they no longer had it. In general, the sandals provided a certain level of comfort and did not interfere with the natural gait when the augmentation was turned off. All users were able to perceive the vibrations at all four locations on each sole, however, the perceived strength differed between users. This is likely due to the differences in body weight, with vibration appearing more prominent for lighter users.

However, the design was not free of flaws (Figure 9). The applied physical stress like scratching the soles over rough surface textures (e.g., asphalt) or getting stuck on the edges of stairs with the tip of the soles caused the glued parts to lose connection (Figure 9 A) and defibering of the 3D printed material on the heel (Figure 9 B). Also, the continuous bending of the soles while walking created crease marks on the top part of the sole (Figure 9 C) and the compression and shear forces inside the soles caused the infill structure to collapse and defiber (Figure 9 D).

To make the sandals more sturdy, we will change the infill pattern from Gyroid to Triangles [49] and increase the infill density from 20% to 35% in future iterations. This will also increase the weight of the 3D printed parts from 134 g to 184 g (top: 112 g, bottom: 72 g).

Sturdiness can be further increased by coating the edges with liquid rubber (mibenco PUR) to seal and protect the edges.

We also found that the tolerance of actuator placement to variations in foot size is low: while a given shoe can fit a range of sizes in practice, deviations smaller than a centimeter can cause misalignment between the shape of the foot and the placement of the actuators. For this, we intend to implement multiple sandals of different sizes for future experimental work. Creating these manually is not optimal, in future we intend to look towards parameterized design tools (e.g., [19, 44]), which might be especially interesting in the context of generative design work (e.g., [16, 41, 42]).

6.2 Design Space

The sandal we designed is not a one-size-fits-all solution, nor is it a general purpose device. Rather it is tailored towards our interests as designers. For example, our choice of relatively high frequency signals, allows us to use a relatively low number of actuators, due to the relatively large receptive fields of the Pacinian corpuscles. However, our approach of mechanical integration still allows for some localization. Finally the actuator we chose has a relatively narrow bandwidth, a concession we made to simplify construction. These are choices made from a design space that include technical considerations such as *actuator properties* and *sensor design* constrained by the *physiological considerations* of human sensing and acting capabilities. It also contains *mechanical considerations* which modulate how sensors and actuators function. Finally, it considers *construction* considerations, which influence the ease of replication.

An observation we made, which we believe is often not explicitly addressed, is that in practice the final choice for sensors, actuators, or design approach is based on *soft* factors, that is, social considerations. These social considerations are rarely discussed, in part because they are implicit, in part because it sounds more scientific to claim *"we chose this actuator due to its resonant frequency"* than to say *"we chose this actuator because it is easy to purchase"*. However, these soft factors are important, and have scientific relevance, in particular when looking towards replicability of experiments, validity of results, and fostering an inclusive and diverse research community.

Presenting this design space is intended not just to help others build their own prototypes, but also as a tool to systematically review differences and similarities between existing prototypes. They will help outline the important differences between a high fidelity and low fidelity device, so that we might better understand what factors are responsible for differences in experimental findings.

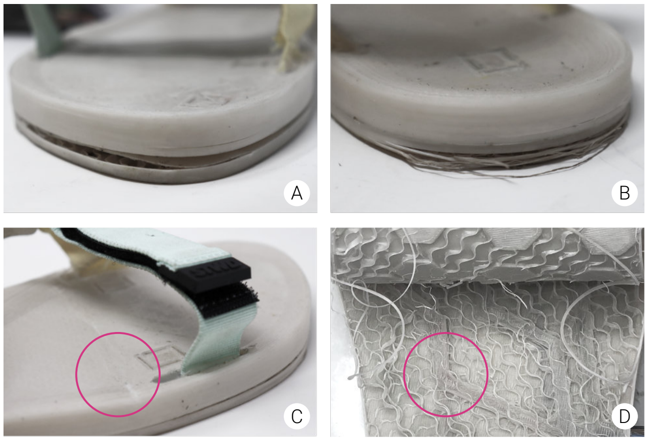

Figure 9: Problems with the first prototype. The outer shell of the print dispersed on the front (A) and especially on the heel (B). (C) Crease marks occurred on the top of the sole at the metatarsals. (D) The infill structure broke.

6.3 Design Diversity

Working with augmented footwear is different from other augmented reality technologies for a number of reasons: visual and acoustic AR and VR has matured to the point where devices are readily available to researchers and consumers alike. Having access to such mature products is beneficial for research as it makes it easy for novices to start engaging with the research area. It also allows experts to deploy their respective studies on the same or similar hardware, which improves the validity, as it reduces the chance that effects are attributed to the design of the device, rather than the specific research question explored.

The technical capabilities of these more matured devices are, however, not the biggest difference to the augmented footwear space. They do not only represent a significant expertise in *how* they are built, but also in *what* to build. This *what* is shaped by years of exploration which has lead to an understanding of the relevant psychophysical factors, such as representation of color spaces in displays, or desired frequency responses of headphones, as well as a consensus between users and designers of the type of content and style of content the devices are optimized for.

Designing augmented footwear then is not just a technical problem, rather it is a massive design challenge, as it is unclear what properties such an augmented shoe should have. There is no consensus on what, specifically, the useful applications, the type and style of content of such a device should be. Will future users want dramatic effects that can be achieved through devices such as LevelUps [54]? Will the more subtle approaches we highlight here be more desirable in everyday life? As these questions are not answered, a "standard" haptic shoe cannot be designed. The biggest problem here is not a technical one, but rather a *soft* problem, based on social norms and expectations.

To address this, we explicitly decided to dedicate a significant amount of effort in communicating the design space, and design considerations which went into creating our prototype sandal. While our prototype is open source, and we invite anyone to copy and build on it, we do not expect it to serve all possible purposes. This is why we provide reflections in the design choices, so that others might learn from our thoughts, even if they decide to design something radically different. While we do not believe that our specific prototype is relevant for all future work in this space, we believe that sharing the underlying considerations will.

In summary, we provided an overview of the design space of vibrotactile interactive shoes for improving VR and AR including a sample implementation from the design space, along with anecdotal reports of experiences the system can evoke. This overview supports researchers in either copying the existing implementation, or help identify how their needs require a different design. This enables researchers to compare and to discuss different approaches and prototypes, and will help in decision-making for the design of future augmented footwear and augmentation approaches. Ultimately, we wish for our contribution to encourage others to engage with this research area, while simultaneously improving the overall quality of research on tactile AR and VR for augmented footwear.

7 CONCLUSION

Augmented Footwear can provide a powerful platform which might act as an alternative or addition to traditional AR and VR systems. However, as this is a comparatively new direction in HCI, there are no products which researchers might build upon, and few shared standards or platforms shared between researchers. We discussed the design space of shoes for augmented tactile reality, highlighting how physiological factors provide a guide for actuator placements and biomechanical factors can guide sensor placement. Mechanical considerations provide further constraints. Finally, we presented an open-source example implementation from this space, which can be used as an experimental platform for vibrotactile rendering and tactile AR. Explorations of such renderings while walking and balancing tasks evoked different experiences in naive users, such as material properties (compliance) or agency. We hope our work will contribute to further diversity and exploration of new and creative ideas in this research area, by lowering the barrier of entry for new researchers. We also hope that this type of work will support the scientific quality of research output in the field by making it easier to compare results between studies.

ACKNOWLEDGMENTS

We would like to thank Ata Otaran and Rishabh Dabral for volunteering in the explorative sessions and sharing their experiences, as well as providing valuable feedback.

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