The Future Smart Shoe: Demonstrating Sensing-to-Actuation Prototypes

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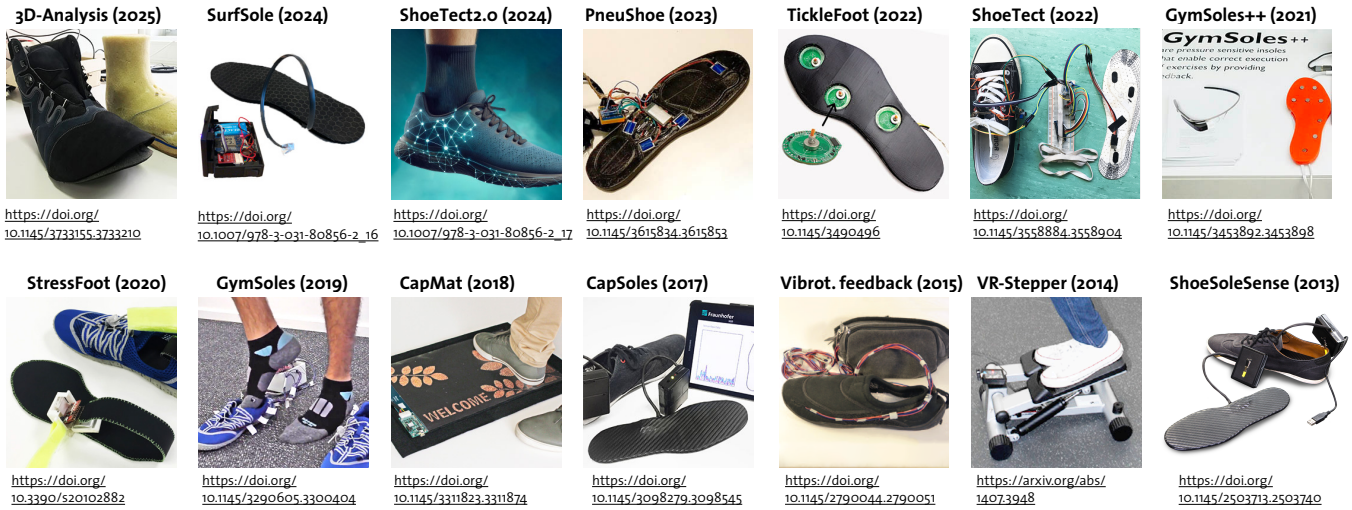

Figure 1: Overview of augmented foot interfaces previously developed by the authors [8, 10, 11, 14, 17, 20–25, 33, 37].

Abstract

The human foot plays still remains underexplored for interactive system design despite its continuous engagement with physical surfaces and movement. Foot-worn interfaces, often integrating sensing and actuation, offer a promising but challenging interaction channel for embodied and in-the-wild experiences, as many of their interaction qualities only emerge through use. This work presents an interactive demonstration of four prototypes that consolidates over a decade of research on smart insole–based augmented foot interfaces into a coherent, experience-driven showcase, enabling attendees to experience and compare different smart footwear.

ACM Reference Format:
Marco Torge Gabrecht, Ruben Schlonsak, Troy Nachtigall, Don Samitha Elvitigala, and Denys J.C. Matthies. 2026. The Future Smart Shoe: Demonstrating Sensing-to-Actuation Prototypes. In *Extended Abstracts of the 2026 CHI Conference on Human Factors in Computing Systems (CHI EA '26), April 13–17, 2026, Barcelona, Spain.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3772363.3799256

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CHI EA '26, Barcelona, Spain

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ACM ISBN 979-8-4007-2281-3/26/04
https://doi.org/10.1145/3772363.3799256

1 Introduction

The human foot plays a central role in locomotion and bodily awareness, yet remains an underexplored site for interactive system design. While hands and eyes dominate most human computer interaction paradigms, the feet continuously engage with physical surfaces, support balance, and mediate rich sensory input during

everyday movement. This makes foot worn interfaces a promising but challenging interaction channel, particularly for embodied, mobile, and in the wild experiences. Designing foot based interfaces has been a long-lasting challenge with unique difficulties. Throughout centuries, footwear evolved from simple sandals up to complex user-case specific interfaces, such as a skiing boot. In HCI, we also denote footwear as so called "Augmented Foot Interfaces" [9]. Meanwhile smart foot interfaces often incorporate both, sensors and actuators. On the one hand, it makes increasingly sense to understand human activity, such as timing, ground contact, terrain context, and physical engagement. On the other hand, embedding actuators into a foot interfaces allows us to transmit information to the user, such as providing a feedback from a virtual environment.

We present an interactive demonstration at CHI'26 that consolidates prototypes from over 10 years of research on foot worn smart insole interfaces. The demo brings together a family of compact, lightweight, and fully untethered prototypes that span a design space from multimodal sensing to embodied actuation.

2 Background

Figure 2: An early foot augmentation - the first football boot, weighting 436g, developed in 1953 by Adidas and debuted by Fritz Walter in 1954 at the FIFA world cup in switzerland [7]. Back then, and to some extent still today, fabricating footwear was a hand craft. The picture on the right shows Adi Dassler, the creator and innovator of Adidas [36].

The design of augmented footwear begins long before any material is cut or printed, as shoe design requires considering complex negotiations [29]. The ideation process is a critical stage in which possibilities are explored, constraints are surfaced, and early concepts are shaped through collaborative creativity. In the context of foot augmentation, this phase benefits from the integration of diverse perspectives: from HCI researchers envisioning interaction possibilities, to footwear designers balancing ergonomics with aesthetics, to material scientists creating entanglements, to athletes and rehabilitation specialists articulating functional demands, such as a functional football boot with spikes (see Figure 2). Speculative design scenarios, low-fidelity mockups, and cross-domain inspiration allow this stage to challenge conventional assumptions about what shoes can do, and for whom. Key to the ideation process is practical making and embodied wearing explorations as shoe and foot-based interfaces often require resilient, flexible materials and user personalization for optimum response [26]. We consider a soccer player who needs a stiff upper for protection and integrated outsole spikes for traction. In contrast, a runner aiming to improve performance raises questions of injury prevention and durability, inspiring designs such as shoes that dynamically adjust stiffness to foot strike to reduce injury while enhancing performance. As scenario-driven ideation makes people ideate for concrete situations, designers also consider social, aesthetic, and ethical aspects.

Wearable art and fashion design provide another rich domain of inspiration for foot augmentation, transforming shoes from merely functional objects into expressive, interactive platforms. The intersection of technology and artistic expression has led to innovative approaches where footwear becomes a canvas for personal creativity and technological integration as seen in the work of Bitonti [3]. Artistic approaches are particularly evident in the development of wearable bio-HCI systems that challenge traditional boundaries between technology and biological materials, opening new possibilities for foot-based interfaces that respond dynamically to user input and environmental conditions [39].

2.1 Fabrication of Augmented Footwear

Moving from concept to physical form requires fabrication workflows that can seamlessly integrate the demands of wearable comfort and rapid mass manufacturing with the precision (see Figure 3). Traditional shoemaking techniques offer proven durability and fit, yet must be reinterpreted to accommodate modern fabrication tools such as multi-material 3D printing, laser cutting, and smart textile weaving. The selection of materials, which are ranging from breathable, flexible fabrics to rigid support structures, must balance competing needs for comfort, mechanical performance, and compatibility with electronics. Further, embedding sensors, actuators, and wiring during fabrication, rather than as afterthoughts, can produce footwear that feels and functions as a coherent whole, rather than a shoe with "add-ons".

Figure 3: In the fabrication workflow, materials are carefully selected and patches prepared before sewing. What was once handcraft became automated with machines such as sewing, lasting, sole stitching, cementing, heel attaching, edge trimming and buffing, and patching and repair machines. The photo shows Adi Dassler in the Adidas factory in Herzogenaurach, Germany [36], where performance shoe production became increasingly automated.

2.2 Material

The selection of materials for foot augmentation requires careful design consideration and negotiation of flexibility, breathability, durability, and thermal compatibility for comfort [30] especially with embedded technology, embedded in the shoe structure so that the human and the technology do not harm each other. Take, for example, recent research in digital manufacturing with silicone-based inks containing cellulose nanocrystals and carbon black fillers can be used for direct ink writing of shoe insoles with embedded

piezoresistive sensors [2]. The choice between different thermoplastic elastomers depends on specific application requirements: some materials offer greater durability and printability for high-performance applications, while others provide superior flexibility and comfort characteristics ideal for extended wear applications. When integrating electronic components, material selection becomes even more critical as the chosen materials must provide adequate protection while maintaining desired mechanical properties. Research has shown that the same flexible material can serve multiple functions – providing structural support, enabling specific deformation patterns, and housing sensing elements or embedding the sensors directly into the shoe sole fabrication [26] is essential. Design notions like Research Products [31] show the importance of fit, finish and shoe design when creating foot augmentations. The development of hybrid manufacturing approaches allows for the combination of multiple materials within a single shoe makes this possible in the HCI research community.

2.3 3D printing & multi-material printing

Over the past decade, 3D printing has evolved from an experimental technique into a feasible technology for manufacturing custom footwear [32]. In HCI research, 3D-printed shoes and components have been explored for both aesthetic expression, leveraging the formal freedom of additive manufacturing [3, 30], and functional performance, particularly pressure distribution and load management to improve comfort [1, 13, 16]. Similarly, 3D printing has been widely adopted for the development of corrective and assistive insoles, enabling customization for specific foot conditions and biomechanical needs [4–6, 40]. Beyond electronics-based interactivity, we also find examples of shoes that remain interactive through their material and structural properties alone. By employing metamaterials and complex internal geometries enabled by 3D printing, these designs can dynamically adapt to the gait, posture, and weight of the wearer without embedded sensors or actuators [15, 18, 38]. Such approaches highlight the potential of multi-material and computational design techniques to embed responsiveness directly into the physical form of footwear.

2.4 Hybrid manufacturing

The combination of traditional shoemaking techniques with additive and subtractive manufacturing creates new possibilities that take advantage of the strengths of both approaches. Research in digital fabrication has demonstrated how hybrid approaches can successfully integrate time-tested craftsmanship methods with precision digital fabrication techniques [27]. This approach is particularly evident in projects where 3D printed soles are combined with traditionally crafted uppers, allowing for customization of the functional elements while maintaining the aesthetic and tactile qualities associated with conventional materials [13]. Digital fabrication tools integrated with traditional processes enable designers to create components that would be impossible to achieve with either method alone. The development of hybrid craft approaches has shown how we can successfully combine digital and analog techniques to create unique artifacts that leverage the benefits of both manufacturing paradigms [19]. Laser cutting precisely patterns leather uppers to match 3D-printed sole geometries, while traditional stitching ensures durability and flexibility [28]. This strategy suits research prototypes and small-batch products where full manufacturing automation is economically unfeasible.

2.5 Embedding electronics

Creating augmented footwear almost always requires embedding electronics. In particular seamlessly integrating sensors, actuators, and wiring into the shoe body is essential to ensure comfort, durability, and overall user satisfaction. Bulky or exposed components will cause discomfort and irritation, so embedding them naturally within the shoe helps maintain a comfortable fit. Proper integration also protects these delicate parts from damage caused by sweat, dirt, impact, or bending, significantly extending their lifespan and reliability. Additionally, a sleek and clean design without visible wires or bulky tech enhances the shoe's aesthetic appeal, making it more attractive to users. Well-integrated components are less likely to shift or fail during movement, ensuring consistent functionality and safety by minimizing risks such as tripping or electrical issues. Ultimately, this thoughtful integration improves the user experience by making smart features feel like a natural part of the shoe rather than an awkward or cumbersome add-on.

3 Demonstrated Prototypes

We are entering a new era of fabricating smart foot wear. In this demo, we would like to demonstrate four novel prototypes to the public. All prototypes will not only be demonstrated but will also be usable by visitors.

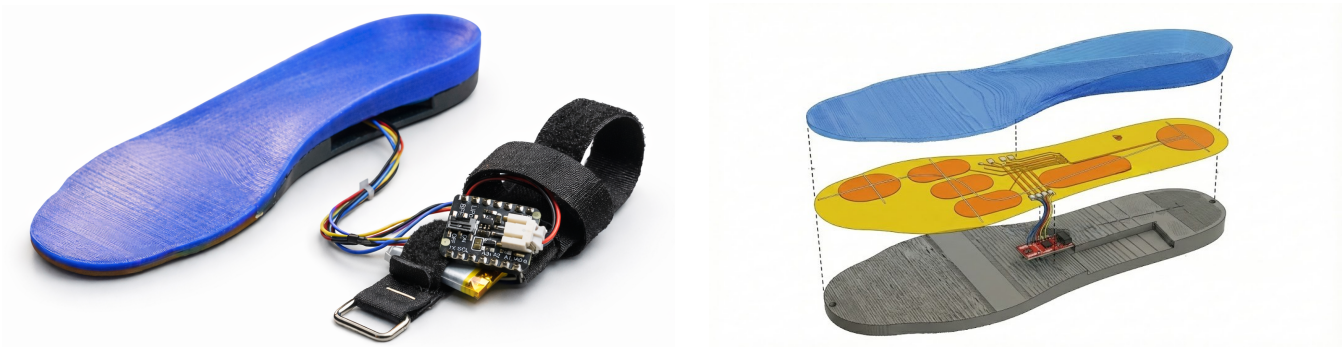

Figure 4: Smart-insole prototype. The sensing layer consists of a sensor foil with six capacitive electrodes read out via an MPR121 capacitive touch controller. Inertial sensing is provided by an LSM6DSV16X IMU (accelerometer + gyroscope), mounted in the electronics module and connected to the insole via a wiring harness.

Figure 5: Prototype overview showing the insole with integrated coin vibration motors, the backside of the midsole, and the fully assembled shoe from the rear. The system integrates an IMU, pressure sensors, solenoid valves, coin vibrators, a battery, an antenna, and a custom PCB hosting the ESP32 and MOSFET stages. A CAD cross-section illustrates the internal structure: inner shell, stabilized air chambers for forefoot and heel, air outtake and interconnection valves, pressure sensors, and dedicated space for the stacked PCB, battery, and external antenna. The insole includes mounting cavities for the vibration motors.

3.1 Real-time Human Activity Recognition Insole

Our first specialized HAR prototype is based on previous research (SurfSole [34, 37], represents smart insole platform based on capacitive sensing for real-time activity recognition. The system was designed to classify ambulation activity, such as walking, running etc. The system is built around a dual-core ESP32-S3 microcontroller (240 MHz, 16 MB flash, 2 MB PSRAM). The ankle-mounted wearable unit connects to an instrumented insole with six capacitive pressure sensors. An onboard 6-axis IMU provides inertial data, resulting in a 12-dimensional sensor vector per sample (Figure 4).

3.2 Pneumatic actuation insole with vibrotactile feedback

This prototype advances wearable foot haptics by combining controllable pneumatic compliance with localized vibrotactile cues in a single, fully integrated insole that operates unthethered. The hardware includes an IMU, Pressure Sensors, Solenoid Valve, Coin Vibrator, Battery, Antenna, and a custom PCB + ESP32 (Figure 5).

3.3 Radar context-sensing smart footwear

The prototype's core integrates an Acconeer XR112 mmWave radar sensor, enabling rich context sensing of the ground surface and the user's motion. Using this radar data, the system feeds trained machine-learning models to classify a variety of terrain types encountered during natural walking, achieving robust surface recognition even under real-world conditions. The same models simultaneously identify motion states such as walking, stepping up, stepping down, and standing still with high accuracy, allowing both terrain and gait to be inferred continuously and reliably from the radar return patterns. This fine-grain awareness of surface and activity supports adaptive, context-aware behaviors beyond traditional inertial or pressure-only sensing (Figure 6).

3.4 3D printed sensors on a textile sole/shoe

This solemaker prototype features a 3D-printed sole as sensor where conductive and non-condutive TPU electrodes are printed directly onto textile circuits, showing the potential for embedding sensing into personalized and fabricated footwear [35] (Figure 7).

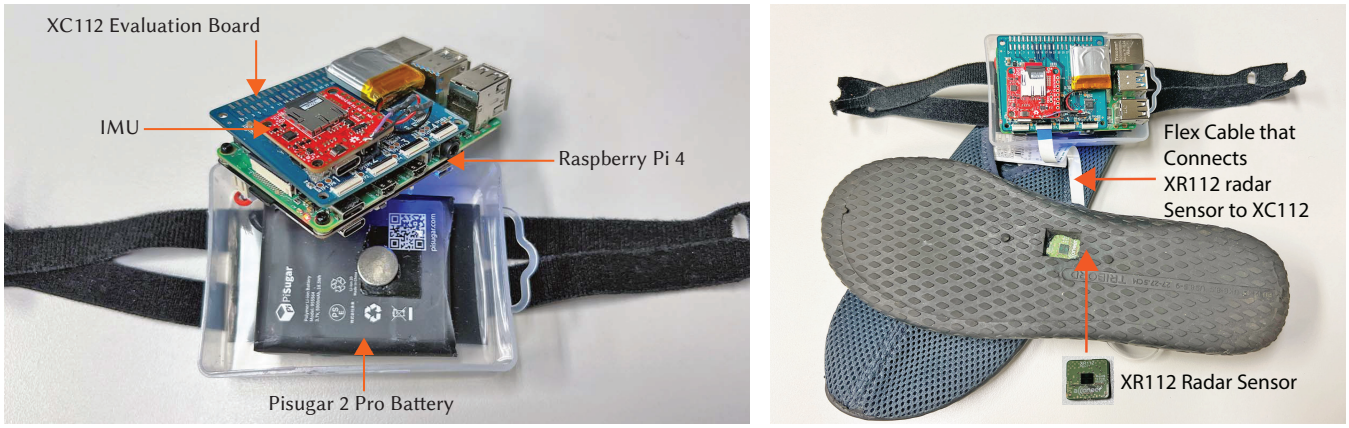

Figure 6: Depicting the prototype: Parts of the controlbox are: the XR112 radar sensor, an XC112 Acconeer evaluation board, a Raspberry Pi 4, a Pisugar 2 Pro battery, and a Sparkfun OpenLog Artemis IMU. [12]

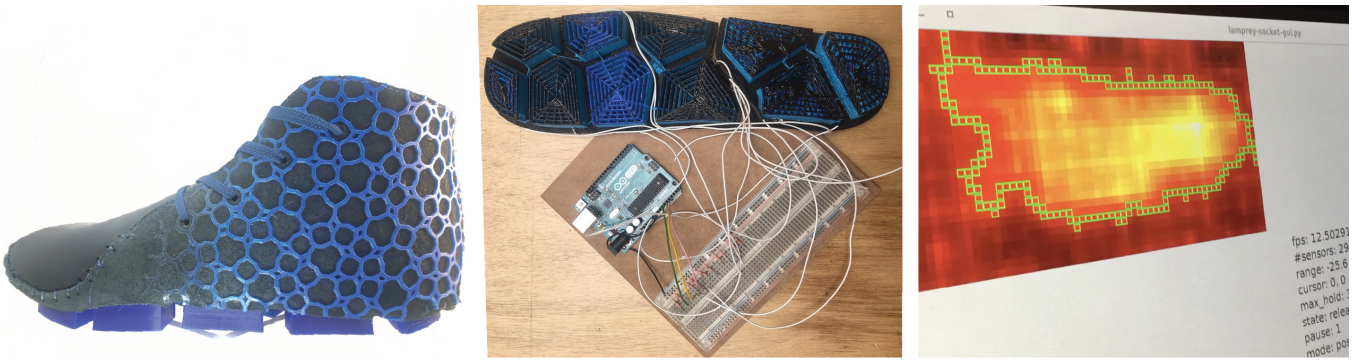

Figure 7: Showcasing a 3D printed sole: conductive woven electrodes are printed with conductive and non-conductive TPU onto smart textile [26], enabling personalized use feedback in smart shoes. An online platform visualizes the pressure data in real-time.

4 Conclusion & Outlook

Based on the past and current research, we conclude that the human foot represents a vital, yet significantly underutilized, frontier in human-computer interaction. This work has consolidated over more than a decade of research into a cohesive demonstration, showcasing "sensing-to-actuation" prototypes. With four novel prototypes showcased, ranging from real-time Human Activity Recognition (HAR) to mmWave radar surface sensing, vibro-/pneumatic actuation mechanisms, and a new way of fabricating sensors directly into the shoe, we demonstrate that the concept of smart footwear is not just an idea, but a reality that is reaching users.

Our findings suggest several key advancements for the future of the field:

- **Multimodal Convergence:** The transition from single-sensor devices to complex systems—incorporating capacitive electrodes, IMUs, pneumatic compliance, and vibrotactile feedback—allows for a more nuanced interpretation of human activity recognition and terrain interaction.
- **Real-Time, Untethered Intelligence:** The successful implementation of on-device inference and compact, fully untethered units proves that sophisticated interactive systems can operate effectively in "in-the-wild" environments.
- **Seamless Fabrication:** The shift toward hybrid manufacturing and multi-material 3D printing enables the direct embedding of electronics into the shoe structure. This ensures that smart features feel like a natural extension of the footwear rather than cumbersome "add-ons," which is critical for user comfort and long-term adoption.
- **Personalization and Accessibility:** Utilizing 3D-printed sensors on textile soles demonstrates a path toward personalized footwear that adapts to a user's specific biomechanical needs and aesthetic preferences.

This interactive CHI'2026 demonstration in Barcelona let users experience the future of smart footwear, which integrates HCI, material science, athletics, and fashion to create expressive, functional interactive shoes.

Acknowledgments

This research is funded by the Federal Ministry of Research, Technology and Space of Germany (03DPC0711A, 16SV9597, 03DPC0716C).

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