Making Gait Visible: Actionable Insights for Augmented Foot Interfaces

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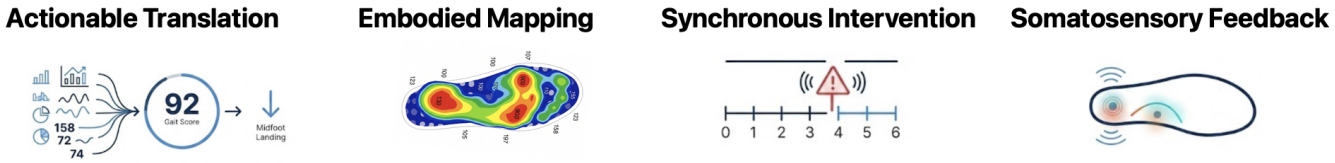


Figure 1: The four primary design requirements for actionable augmented foot interfaces derived from our thematic analysis: (1) translating raw metrics into actionable directives, (2) mapping data to embodied somatosensory perception, (3) timing interventions synchronously within the active biomechanical cycle, and (4) delivering proactive, localized haptic bio-feedback.

Abstract

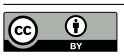
Despite hardware advancements in smart footwear, translating complex biomechanical data into actionable insights remains a critical challenge in Bio-HCI. Current systems often overwhelm users with raw metrics, creating an actionability gap. To address this, we conducted a two-phase User-Centered Design approach. A formative qualitative study with 10 athletes revealed profound cognitive overload from raw data, a strong need for somatosensory translation, and a demand for proactive, real-time vibrotactile intervention over retrospective dashboards. Second, an expert walkthrough with an orthopedic specialists validated the concept of translating this data into more actionable insights. Based on these insights, we propose a generalized design framework for smart footwear that shifts the paradigm from passive data collection to closed-loop, somatosensory bio-feedback. By providing real-time, embodied interventions, this approach bridges the gap between clinical diagnostics and preventive health, laying the foundation for actionable augmented foot interfaces.

CCS Concepts

• **Human-centered computing** → **Empirical studies in ubiquitous and mobile computing**; **Interaction design theory, concepts and paradigms**.

Keywords

Smart Footwear, Bio-HCI, Actionable Insights, Augmented Foot Interfaces



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1 Introduction

The field of Biological Human-Computer Interaction (Bio-HCI) continuously strives to develop a deeper understanding of the human body as a biological system [36]. While hands and eyes dominate most HCI paradigms, the feet continuously engage with physical surfaces, support balance, and mediate rich sensory input during everyday movement [32]. This makes smart footwear a promising but challenging interaction channel, particularly for embodied, mobile, and in-the-wild experiences [31]. Designing smart footwear has been a long-lasting challenge with unique difficulties, yet it remains one of the most critical frontiers for ubiquitous computing [22].

Concurrently, hardware for smart footwear is evolving at a rapid pace [1]. Unlike ubiquitous wrist-worn devices that often rely on secondary proxies for lower-body movement, smart insoles offer the opportunity to capture significantly more precise and direct biomechanical data at the source of ground contact. Recent developments in smart insoles have demonstrated the viability of wireless, multimodal sensing systems capable of complex, on-device inference [21]. These systems can capture high-dimensional biomechanical data in the wild, traditionally restricted to clinical gait analysis laboratories [33]. This presents unprecedented opportunities to deploy non-invasive technology that seamlessly integrates into daily routines of people. In HCI, we denote such advanced footwear as augmented foot interfaces [9], integrating both sensors and actuators [7] to simultaneously capture rich human activity data [11, 13] and deliver real-time haptic feedback directly to the user [10, 25]

However, despite these hardware leaps, a significant actionability gap remains [4]. The grand challenge lies in translating complex, laboratory-grade data into intuitive, actionable insights that users can confidently rely on and act upon [15]. Smart insoles capture high-fidelity biomechanical data but leave users alone with incomprehensible raw outputs [27]. This fundamental disconnect, where systems collect precise data but fail to present it in a format users can intuitively translate into spontaneous physical correction. Instead of prompting behavioral adaptation, this data overload leads to user fatigue and system abandonment [2]. Consequently, current smart footwear acts as a passive diagnostic mirror rather than an active, experiential interface [12]. To overcome this gap and elevate smart footwear into true augmented foot interfaces, the interaction paradigm must shift from passive data collection to active, bidirectional communication. This requires designing actionable insights [14, 18]: translating high-dimensional sensor data into forms that reduce cognitive load and reflect actual bodily sensation.

In this paper, we explore the user experience of biomechanical data interpretation [5] and present a generalized user-centered HCI framework for augmented foot interfaces. To bridge the actionability gap, we propose four design recommendations. Drawing on insights from qualitative interviews with athletes, we identify the primary pain points of users and establish design requirements for translating complex lab data into intuitive, closed-loop HCI systems [28]. Consequently, we formulate the following research questions: **RQ1:** What are the information needs, expectations, and frustrations experienced by ambitious recreational athletes when using current wearables? **RQ2:** How must user-centered interfaces (UX/UI) for smart insoles be designed to successfully translate abstract biomechanical sensor data into actionable insights?

2 Related Work

Recent innovations have pushed foot-based sensing far beyond simple accelerometry, establishing a rich ecosystem of augmented foot interfaces [9]. Researchers have developed highly sophisticated modalities to capture granular ground-interaction data, utilizing capacitive sensing grids [23, 24], pneumatic chambers [13], mmWave radar [11], and multi-sensor FSR arrays [19]. These hardware leaps provide an unprecedented foundation of contextual, clinical-grade biomechanical data directly from the user's everyday environment. However, despite this wealth of data, early stage-based models of self-tracking [18] indicate a consistent breakdown between the collection and action phases [4]. Users can easily accumulate massive datasets, but struggle to integrate raw biomechanical metrics into their "lived" bodily routines [12, 28]. In the context of sports wearables, raw pressure maps and exact pronation angles frequently induce cognitive overload. The challenge therefore lies not in improving sensor accuracy, but in designing HCI translation layers that convert abstract data into intuitive, spontaneous correction mechanisms. To ultimately close this interaction loop, researchers have recently explored foot-based actuation to deliver somatosensory stimuli directly to the wearer. vibrotactile feedback has been successfully utilized for navigation [22, 25], affective interaction [8], and real-time athletic correction [9, 10]. Looking beyond immediate vibrotactile feedback, the intersection of biomechanics and material science is opening new avenues for personalized physical adaptation via 3D and 4D printed footwear [3, 6, 16, 17, 20, 26, 35]. Our work builds on these foundations by proposing a framework that unites high-fidelity sensing, embodied visualization, and localized actuation into an actionable user experience.

3 Methodology

We followed a User-Centered Design (UCD) approach, structured into two iterative phases to ensure the system is both medically sound and highly actionable for the end user. To inform the design of actionable augmented foot interfaces, we sought to understand how atheltes interact with, interpret, and experience friction with current biomechanical tracking systems.

Phase 1: Needfinding and Problem Space. To understand the context of use, we conducted a formative qualitative study focusing on the "pain points" of current wearables. We recruited 10 athletes (6 female, 4 male; ages 21–34, $M = 26.5$, $SD = 4.1$) representing a diverse range of disciplines, including long-distance running, sprinting, trail running, and weightlifting. All participants had prior experience using sports wearables (e.g., smartwatches, foot pods) and some had a history of minor lower-limb sports injuries (e.g., plantar fasciitis, shin splints), making them highly motivated to understand their gait mechanics. The participant demographics and their profiles are summarized in Table 1.

Table 1: Participant Demographics and Profiles

ID	Age	Gender	Sport	Time
P1	24	F	Weightlift	58m
P2	21	F	Distance	62m
P3	27	M	Crossfit	61m
P4	34	F	Triathlon	73m
P5	23	F	Crossfit	52m
P6	28	F	Running	59m
P7	26	M	Sprinting	48m
P8	22	F	Sprinting	47m
P9	31	M	Trail run	67m
P10	29	M	Trail run	71m

The study consisted of in-person sessions lasting between 45 and 75 minutes (averaging approx. 59 minutes). We employed a "think-aloud" protocol combined with a semi-structured interview. Participants were presented with raw data outputs generated from state-of-the-art clinical smart insoles (e.g., dynamic plantar pressure heatmaps, IMU-derived pronation angles, and strike distribution graphs). We asked participants to interpret the data, describe what actions they would take based on it, and articulate their frustrations. Finally, we engaged them in a participatory design exercise to sketch their ideal feedback mechanisms. Early findings indicated a strong desire for preemptive injury warnings rather than post-workout statistics. All sessions were audio-recorded and transcribed verbatim. We analyzed the transcripts using inductive thematic analysis. Two researchers independently coded the data, generating initial codes related to data literacy, physical sensation, and feedback timing. Through iterative discussion, these codes were synthesized into overarching themes representing core pain points.

Phase 2: Formative Evaluation. To ensure clinical validity, we conducted an initial expert walkthrough of the UX concept with specialists from orthopedic practice (in collaboration with a clinical partner). This phase evaluated whether the visualized actionable insights are medically sensible from a biomechanical perspective, while remaining easily interpretable for the lay user. The experts validated our concept, for instance confirming that simplifying complex force-vectors into a "fatigue heat map" maintained medical integrity while drastically reducing cognitive load.

4 Findings and Design Requirements

Our thematic analysis of the interview transcripts and think-aloud sessions revealed a profound disconnect between the high-fidelity data currently collected by smart wearables and the actual comprehension and integration of that data by athletes. Rather than empowering the users, the influx of raw metrics often paralyzed their decision-making. We structured our findings into four primary themes, supported by extensive participant quotes, which directly inform our design requirements for actionable augmented foot interfaces

4.1 The Black Box of Biomechanics and Cognitive Overload

When participants were presented with traditional clinical data outputs—such as multi-colored plantar pressure heatmaps or line graphs showing exact pronation degrees, they uniformly reported severe cognitive overload. The prevailing sentiment was that current systems demand a level of biomechanical literacy that lay athletes simply do not possess. The data felt abstracted, mathematical, and entirely disconnected from their physical reality. One participant, a triathlete with a history of metatarsal stress fractures, articulated the anxiety this abstraction caused: *"I'm staring at this heat map, and I see a big red spot on my forefoot. Okay, great. Does that mean I'm running efficiently because I'm on my toes, or does it mean I'm going to fracture a metatarsal again? It's completely opaque to me. It's just noise, and honestly, it makes me more anxious than if I hadn't seen it."* (P4). Similarly, athletes felt that the granularity of the data was practically useless for real-world application. One participant, a sprinter who had been trying to correct an asymmetrical gait, highlighted the translation failure of exact measurements: *"Telling me my pronation angle is 8 degrees on the left and 4 degrees on the right is mathematically precise, sure. But it is practically useless. I don't speak 'degrees' when I run. I don't know how to consciously adjust my ankle by exactly 4 degrees at a full sprint. I need to know what to do, not just what the math says."* (P7). One participant, a weightlifter trying to balance her center of pressure during heavy squats, echoed this sentiment: *"I get these post-workout graphs showing my weight shifted 12% to the left heel. But looking at it as a pie chart does absolutely nothing for my form on the floor. It's a black box."* (P1).

Requirement 1 (Actionable Translation): Systems must move beyond raw data presentation. Interfaces should compute an actionable gait score or provide explicit, contextual directives. The system must translate diagnostic metrics into clear behavioral instructions rather than leaving the heavy burden of interpretation entirely on the user.

4.2 The Need for Somatosensory Trust (Digital Twin)

When discussing potential solutions, participants emphasized that visual data displayed on a 2D smartphone screen felt fundamentally disconnected from the 3D physical sensation of their feet [30]. They articulated a strong desire for a "translation layer" that mapped the data directly to their bodily perception. The concept of a digital twin, a simplified presentation of their foot that they could view and manipulate, resonated strongly with almost all participants. One participant stated: *"When I run, I don't see my feet, I feel them. If I could look at an app and see a 3D model of my foot lighting up exactly where I feel the pressure building, I guess I would trust it more easily. It connects the math to my actual physical sensation. [...] Right now, I don't trust the graphs because they don't look like my body."* (P2). One participant, an ultra-marathoner accustomed to managing pain on long trails, noted the discrepancy between somatic feeling and digital reporting: *"There is a huge gap between the graph on my phone and the ache in my arch. The system needs to speak the language of the body. If the app showed a glowing 3D foot where the glow matches the burning in my plantar fascia, I would immediately know what the data meant."* (P10). One participant, returning from an achilles injury, emphasized the emotional reassurance a digital twin could provide: *"I'm constantly worried I'm favoring my right side. If I had a virtual version of my feet on my phone that mirrored exactly how my weight was landing, it would give me peace of mind.* (P6).

Requirement 2 (Embodied Mapping): Smart footwear must provide embodied mapping via the digital twin. By presenting a dynamic digital twin that visually reflects somatic sensations rather than abstract charts, systems can build user trust, lower the cognitive barrier to data comprehension, and bridge the gap between digital representation and physical feeling.

4.3 The Fallacy of Retrospective Dashboards

Participants were highly critical of the timing of current self-tracking systems. Reviewing a dashboard post-workout was seen as too late for injury prevention or technique correction [34]. By the time they viewed the data, the problematic movement had already been repeated thousands of times. One participant expressed: *"Don't tell me after a 10K run that my form broke down on mile four. By then, the damage is done. My knees already hurt. I want the shoe to tell me during mile four so I can fix it."* (P9). One participant, a crossfitter, explained how post-hoc data fails in dynamic environments: *"I looked at my step data after a heavy lifting session and saw my balance was off. Okay, cool, but I can't travel back in time to fix that lift."* (P3). One participant noted the danger of relying on memory to correct form based on old data: *"If the app tells me I was over-striding yesterday, I try to overcompensate today. But then I'm just guessing. I need feedback while the foot is actually striking the ground, otherwise I'm just creating new bad habits trying to fix the old ones."* (P8).

Requirement 3 (Synchronous Intervention Timing): Feedback must be delivered synchronously with the activity. Post-workout dashboards are insufficient for injury prevention; systems must identify anomalies and intervene within the exact biomechanical cycle they occur.

4.4 Proactive Real-Time Somatosensory Bio-Feedback

Building on the need for synchronous timing, participants stressed that visual or audio feedback during an activity was often dangerous, impractical, or easily ignored. They demanded real-time, proactive interventions delivered through the body itself—specifically, through the feet [29]. One participant stated: *"If my knee is collapsing inwards, I want the sole to literally push back or vibrate to wake up those muscles. Visual warnings are useless when I'm focused on navigating a rocky trail. If my phone buzzes in my pocket, I ignore it. But if my right arch vibrates as I step, I could imagine my brain will fix the step instantly."* (P5). One participant, expanding on this, requested a conversational relationship with the shoe: *"It should feel like a tap on the shoulder. If I start heel-striking because I'm tired, just give me a little buzz on the heel. It's a physical reminder to lean forward. I don't want to look at a screen; I want my shoe to talk to my foot."* (P9). One participant discussed the potential for haptics to serve as an unconscious guide: *"If the vibration is subtle enough, maybe I wouldn't even have to think about it. My body would just naturally shift away from the buzzing. That would be the ultimate wearable, [...] one that fixes my form without me having to interrupt my flow."* (P2).

Requirement 4 (Real-Time Somatosensory Bio-Feedback): To fully close the interaction loop, smart footwear must employ localized, real-time somatosensory feedback (e.g., vibrotactile or pneumatic actuators). Delivering feedback directly to the site of the anomaly through the plantar fascia allows for spontaneous, almost unconscious physical correction, bypassing the need for visual attention.

5 System Concept: Actionable Augmented Foot Interface Concept

Based on the design requirements, we conceptualized an actionable augmented foot interface concept that bridges the gap between passive sensing and active, embodied intervention. Our proposed framework assumes an underlying hardware architecture utilizing a combination of capacitive sensing grids and localized IMUs to capture high-fidelity gait patterns. However, instead of outputting these metrics directly, the backend algorithm processes the data into a simplified fatigue vector. This vector drives the primary UI component: the digital twin. The digital twin is a 3D avatar on the user's mobile device that visually mirrors the user's foot. When the system detects excessive pronation or an anomalous strike pattern, the digital twin highlights the corresponding anatomical zone (e.g., the medial arch) with an intuitive color gradient indicating stress severity. This satisfies Requirement 2 (Embodied Mapping), allowing the user to map visual feedback directly to their proprioceptive sense. To address Requirement 3 (Proactive Interventions), the framework integrates localized vibrotactile actuators distributed across the plantar fascia region. When the system detects a sustained breakdown in form—such as heavy heel striking during fatigue—it triggers a subtle, localized vibration precisely at the site of the anomaly. This creates a closed-loop somatosensory circuit: the foot performs the action, the sensor detects the error, and the actuator immediately cues the foot to correct itself, bypassing the need for visual attention during the activity.

6 Discussion and Design Implications

The primary outcome of this work is a set of Design Guidelines for Wearable Bio-HCI, heavily emphasizing the necessity of actionable insights over pure data dashboards. Our findings strongly suggest that the bottleneck in smart footwear is no longer hardware capability, but rather data legibility. Systems that fail to translate raw data into actionable insights are destined for abandonment. Our proposed conceptual framework demonstrates that by abstracting mathematical precision in favor of embodied, qualitative cues (the digital twin and vibrotactile cues), we can significantly increase user compliance and understanding. Furthermore, this UX concept acts as a foundation for future circular economy and hardware-as-a-service models in wearables. By tracking longitudinal wear and tear alongside biomechanical degradation, such a framework can proactively inform the user when their footwear is no longer providing adequate support. By establishing user trust through intuitive feedback, we lay the groundwork for fully closed-loop hardware systems. In the near future, the data gathered by the digital twin will not only guide user behavior but directly control the physical adaptation and automated 3D-printing of consumable hardware components [26]. A user could receive an alert from their digital twin indicating asymmetrical wear, accompanied by an automated order for a replacement insole parametrically designed (via 3D printing) to correct their specific gait anomaly [3, 6]. This shifts footwear from a static product to a dynamic, iterative service. While this conceptual design successfully addresses user pain points, the real-world deployment of highly dense actuator arrays in thin insoles presents significant engineering challenges related to durability and power consumption. Future work will involve conducting longitudinal, in-the-wild studies with a fully functional hardware prototype to evaluate the long-term efficacy of somatosensory bio-feedback on injury reduction.

7 Conclusion

In this paper, we explored the intersection of self-tracking and augmented foot interfaces to address the actionability gap in smart footwear. Through a qualitative study with 10 athletes, integrated into a robust UCD process, we demonstrated that the primary barrier to effective smart footwear is not sensor accuracy, but the HCI translation layer. Users struggle with the black box of biomechanics and demand proactive, embodied feedback over retrospective dashboards. By designing systems that prioritize actionable translation, embodied mapping via a digital twin, and real-time somatosensory bio-feedback, we can transition smart footwear from passive diagnostic tools into active, closed-loop ecosystems. Ultimately, our work lays the conceptual foundation for next-generation circular wearables, seamlessly integrating data-driven physical adaptation into the user's lived bodily experience.

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