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FootSense: An AI-Augmented Foot-Tactile System for Emotion and Social Regulation in Pervasive Health Contexts

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Abstract

INTRODUCTION: FootSense proposes a novel approach to emotional and social regulation through foot-tactile feedback in public spaces. Unlike conventional upper-body haptic systems, it utilizes the feet as a discreet, low-interference interface. By integrating rhythmic, directional, and social-cue tactile stimulation, FootSense modulates emotional states and enhances social interactions in dynamic environments.
OBJECTIVES: This study aims to develop and validate a multi-mechanism foot-tactile model that facilitates emotional relief and social approach in real-world public settings.
METHODS: We developed FootSense, an AI-augmented ambient intelligence system combining behavioral sensing, contextual inference, and adaptive tactile feedback. A two-week field experiment (N=200, five groups) was conducted across four public environments—mall, campus, hospital, and transit hub—to compare rhythmic, directional, and fusion tactile modes. Data were analyzed via ANOVA, mixed-effects modeling, and correlation analysis.
RESULTS: Rhythmic feedback reduced state anxiety (ΔSAI = –7.5, p<.01), directional feedback increased social approach (+83% vs. control, p<.01), and fusion mode showed the strongest overall effects (ΔSAI = –9.3, p<.001; +121% approach frequency). Tactile activation frequency correlated with improvements (r=.46–.51, p<.05). Environmental factors (noise, crowd density) moderated outcomes, with greater benefits in high-stress settings.
CONCLUSION: Embodied, AI-driven foot-tactile feedback offers an effective low-intrusion intervention for emotion regulation and social engagement across diverse public contexts. This work provides a theoretical and practical foundation for integrating AI-augmented haptics into pervasive health and human-centered urban design.

Keywords: foot-tactile interaction; AI-augmented ambient intelligence; emotional regulation; social approach behavior; multi-mechanism model; wearable haptic system; digital health intervention

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1. Introduction

With the acceleration of urbanization, social interactions in public spaces have gradually diminished, and individuals' daily social behaviors have become more isolated, a phenomenon referred to as the "disappearance of nearby" [1].

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Mental health issues such as social isolation, environmental uncertainty, and emotional anxiety have become increasingly prominent. Existing research indicates a significant correlation between reduced social connection and psychological problems like anxiety and depression [2][3][4]. These issues not only affect individuals' quality of life but also impact public space usage and social interactions.

Tactile interaction, a low-interference, persistent form of feedback, has made significant strides in emotional regulation and behavioral intervention. Rhythmic tactile stimulation has been proven effective in reducing autonomic nervous system arousal and alleviating anxiety [5]. Directional tactile feedback improves spatial predictability and reduces hesitation in movement [6], while social cue-based tactile feedback enhances sensitivity to social cues, promoting social approach behavior [7]. However, most studies focus on upper limb or hand-held devices, leaving foot tactile feedback, especially in real-world scenarios, underexplored.

The foot, as the body part most frequently in contact with the environment, remains underexplored in terms of its role in emotional and behavioral regulation. While existing literature on foot tactile feedback is sparse, its mechanisms in emotional regulation and social facilitation lack systematic research, particularly empirical validation in natural settings. Therefore, exploring foot-tactile feedback for emotional and social regulation in public spaces is of significant theoretical and practical importance.

FootSense is an AI-augmented system that integrates foot-tactile feedback for emotional and social regulation. This system serves not only as a hardware device but also as an emotional intermediary embedded in physical spaces, bridging the gap between digital interaction and embodied experiences in urban environments [5].

This study proposes the FootSense system, which uses three types of foot-based tactile feedback modes—rhythmic, directional, and social cue-based—and validates their effects on emotional regulation and social facilitation through real-world experiments. Based on a three-pathway tactile model of "rhythmic regulation–spatial predictability–social cue sensitivity," this study aims to address the gap in foot-tactile feedback application in public settings, offering a new intervention pathway for digital health and emotional support technologies.

This approach draws on three complementary frameworks: Ambient Urban Computing, Social Computing, and Psychological Intervention Design. FootSense transforms urban infrastructure, such as public seating and sidewalks, into responsive interfaces that collect pedestrian data and provide feedback, altering people's perceptions of public spaces. Previous studies, including Zhang et al. [6], who demonstrated the feasibility of foot-based sensing for stabilization in robotic systems, and Luckins [7], who explored how urban noise could be converted into interactive musical interfaces, support this notion by illustrating the integration of physical space with digital information.

FootSense introduces a novel approach to emotional and social regulation by utilizing foot-tactile feedback in public spaces. Unlike traditional wearable systems that focus on upper-limb or torso feedback for emotional regulation [5], FootSense uses the feet as a discreet and low-interference sensory interface. This innovation enables continuous feedback without disrupting users' daily activities. By leveraging rhythmic foot-tactile feedback, FootSense modulates emotional states, enhances social interactions, and facilitates behavioral guidance without distracting users from their surroundings.

While previous work in embodied cognition, affective haptics, and social facilitation has shown that bodily feedback can influence emotional and social states, existing frameworks typically focus on a single regulatory function or remain at a descriptive level without clear operationalization. This study formalizes foot-tactile interaction as a multi-pathway design framework. We explicitly map different tactile patterns to distinct psychological mechanisms—namely rhythmic regulation, spatial predictability, and social cue sensitivity—and empirically test this framework in a real public environment.

Importantly, this work does not aim to introduce a new sensory modality or replace existing theories in embodied cognition. Rather, it provides a mechanism-oriented synthesis that clarifies how heterogeneous tactile interventions can be systematically designed, combined, and evaluated within an ambient, foot-based interaction paradigm.

2. Literature Review

2.1. Digital Health and Emotional Regulation

Digital health technology has expanded from disease management to encompass emotional regulation and behavioral intervention [5]. Research demonstrates that physiological feedback delivered via wearable devices can effectively alleviate anxiety and stress [8]. Among intervention methods, haptic feedback, which modulates the autonomic nervous system through rhythmic stimulation, serves as one effective means of reducing physiological arousal levels [9]. While traditional wearable haptic systems have focused on emotional regulation through upper-limb or torso feedback [10], these systems are often more conspicuous and less adaptable in social environments. FootSense differentiates itself by employing foot-tactile feedback, a modality that is less intrusive and more suitable for continuous interaction in dynamic public settings. Unlike upper-limb feedback, which may disrupt normal activities or social interactions, foot-based feedback operates discreetly and effectively without drawing attention. This unique aspect of FootSense allows it to provide non-intrusive emotional regulation, making it an ideal solution for use in crowded or public spaces.

FootSense leverages rhythmic tactile feedback as an effective means of emotion regulation, tapping into the autonomic nervous system. While previous studies have primarily focused on upper limbs and torso [10], the potential of foot tactile feedback — a low-interference, highly environment-coupled channel — remains underexplored in emotional regulation. Recent research, such as Albuquerque and Cardoso [11], has demonstrated that mechanical tactile stimulation can significantly impact heart rate variability (HRV), a key marker of parasympathetic activity, providing the physiological foundation for using foot-tactile feedback as an emotion regulation tool. These findings further highlight the efficacy of rhythmic tactile feedback in reducing physiological arousal and promoting relaxation.

Additionally, FootSense integrates principles from Ambient Urban Computing, where urban infrastructure is not just a backdrop but an active computational platform. Previous work by Guttentag demonstrated how citizens, as mobile sensors, contribute to urban heatmaps, a concept that FootSense adopts to gather real-time data from urban environments and transform it into interactive, personalized feedback.

2.2 Social Computer

Spatial uncertainty can induce hesitation in movement and increase psychological load, whereas spatial cues effectively enhance environmental predictability [12]. Haptic feedback offers unique advantages in providing spatial guidance due to its independence from visual attention. While this characteristic has been widely utilized and validated in the field of navigation assistance for the blind [13], the mechanism by which it enhances spatial predictability and reduces hesitation is equally applicable to sighted users navigating complex environmental information. Applying such directional tactile cues to the general population can function as a lightweight ambient aid, fostering more confident movement in public spaces. Furthermore, haptics can reinforce subtle social cues present in the environment [14], thereby promoting more proactive social approach behaviors [15]. This concept is supported by Ding et al. [16], who showed that foot-tactile feedback can be used covertly in crowded settings, such as meetings, to provide private notifications without disturbing others. Similarly, Hatscher et al. [17] explored how foot-tactile cues could control medical equipment in sterile environments, demonstrating the non-intrusive and reliable nature of foot-based interaction. These studies highlight the potential of foot-tactile feedback to serve as an effective, non-intrusive form of communication in both private and public contexts.

2.3 The Potential and Neurophysiological Basis of Foot Haptics

Foot-tactile feedback is gaining recognition in interaction design due to its ability to discretely modulate emotional and physiological responses. The foot, with its excellent sensitivity to different frequencies, rhythms, and directional patterns [18], is particularly suited for providing non-intrusive feedback. While traditional upper-limb feedback systems are often more conspicuous and can disrupt social interactions, foot-tactile feedback offers a subtle alternative that allows for continuous, unobtrusive emotional regulation.

Studies have shown that rhythmic foot-tactile stimulation can effectively modulate autonomic nervous system activity. Specifically, it enhances parasympathetic regulation, as evidenced by increased heart rate variability (HRV) [19], a key marker of parasympathetic activation. This physiological effect underpins FootSense's ability to regulate emotional states and promote relaxation without distracting users from their surroundings. Research by Albuquerque and Cardoso [20] confirmed that mechanical tactile stimulation enhances emotional regulation by influencing HRV, while Zhang [21] explored how rhythmic tactile feedback can synchronize physiological processes, alleviating anxiety and enhancing emotional well-being.

FootSense capitalizes on these principles by providing a low-interference, non-visual communication channel that is seamlessly integrated into everyday activities. Unlike systems that rely on more intrusive feedback modalities, foot-tactile feedback is both discreet and effective, allowing users to remain engaged in their environment while benefiting from emotional regulation. This unique feature of FootSense positions it as an ideal solution for public spaces, where subtlety and non-intrusiveness are key.

2.3.1 The Potential of Foot Haptics in Human-Computer Interaction

Foot haptics is gaining recognition in interaction design due to the foot's ability to distinguish frequencies, rhythms, and directional patterns. The foot's plantar surface is sensitive to low- and mid-frequency vibrotactile stimuli, which can encode discrete patterns despite having lower spatial resolution compared to fingertips. This makes it effective for conveying directional cues with fewer actuators[22].

Recent studies have shown that rhythmic foot-tactile stimulation can modulate the autonomic nervous system by activating parasympathetic pathways. Albuquerque and Cardoso[11] reviewed studies showing that mechanical tactile stimulation improves heart rate variability (HRV), a key marker for emotional regulation. Similarly, Zhang [20] demonstrated that rhythmic tactile feedback synchronizes physiological processes to alleviate anxiety, supporting the use of foot-tactile feedback for emotional regulation.

Foot haptics also offers unique advantages in human-computer interaction, providing a non-visual, non-auditory channel that integrates seamlessly into daily activities. Unlike hand or torso-based haptic systems, foot feedback is less intrusive, allowing users to engage with digital systems without sensory overload, enhancing the overall user experience in ambient settings.

2.3.2 Neurophysiological Mechanisms of Foot-Tactile Emotional Regulation

Foot-tactile feedback is supported by neurophysiological evidence showing that the plantar skin is densely populated with mechanoreceptors that send somatosensory signals to the brain [11]. These signals activate core emotional brain regions, including the anterior insula and anterior cingulate cortex, which integrate bodily states with emotional processing [20, 18]. This direct engagement of emotional brain circuits enables foot-tactile input to facilitate emotional regulation rather than just sensory processing.

Research has shown that rhythmic plantar stimulation can modulate the Autonomic Nervous System, particularly by increasing Heart Rate Variability (HRV), a key marker of parasympathetic activity, promoting physiological relaxation [19, 22]. This mechanism supports the pathway of "rhythmic tactile → autonomic synchronization → anxiety reduction," where bottom-up bodily signals gradually influence emotional experience and reduce stress.

Additionally, interventions like foot massage have been found to increase serum oxytocin levels and activate brain areas associated with emotional regulation, inducing relaxation and positive emotional states [23]. In public-space interventions, even subtle foot-tactile stimulation may shift the user toward a more affiliative, socially open state, complementing the behavioral effects of spatial and social cues.

Together, these findings provide a neuropsychological framework that links foot-tactile stimulation to emotional brain centers and autonomic responses. However, further research is needed to systematically explore how these neurophysiological mechanisms can be applied in real-world public spaces, as most current studies are limited to controlled laboratory environments.

2.3.3 Physiological Indicators and Measurement Perspectives in Digital Health Haptics

Existing research has shown that emotional and social states are accompanied by measurable shifts in physiological indicators, particularly those reflecting Autonomic Nervous System activity. HRV is a key index for parasympathetic regulation [22], while electrodermal activity (EDA) reflects sympathetic arousal[19]. Recent design innovations in wearable skin conductance sensors, such as micro-lace electrode architectures, have improved long-term EDA acquisition robustness and enabled integrated monitoring of both physical and mental activity states [24]. Functional near-infrared spectroscopy (fNIRS) has also been used to capture hemodynamic responses in emotional processing regions [23]. These indicators offer a promising approach for validating the internal mechanisms of foot-tactile feedback and its impact on emotional regulation.

In the context of foot-tactile interaction, these physiological indicators provide a promising window for validating the internal mechanisms of our multi-pathway model. Rhythmic tactile patterns can be linked to HRV changes and reduced physiological arousal; directional patterns may be associated with more efficient spatial exploration and reduced uncertainty-related arousal; and social-cue patterns could be examined in relation to EDA responses and prefrontal activation during approach–avoidance decisions.

2.4 Research Gaps and Contributions of This Study

In summary, despite existing evidence for the effectiveness of haptic feedback and its neurophysiological underpinnings, significant research gaps persist:

- No work has yet integrated three functionally distinguishable mechanisms of rhythmic regulation, spatial predictability, and social cue sensitivity to investigate their combined effects within the unified context of foot-tactile interaction.
- There is a lack of systematic behavioral experiments conducted in real public spaces based on this multi-mechanism framework to examine its efficacy in promoting emotional and social outcomes for the general population.
- Most existing studies focus either on behavioral outcomes or on physiological indices in isolation; few have jointly modeled how Autonomic Nervous System markers mediate the relationship between foot-tactile stimulation and emotional or social changes in ecologically valid environments.

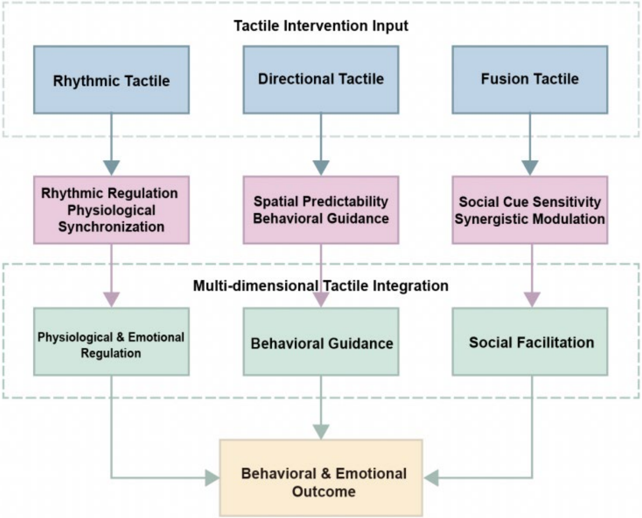

Figure 1. Multi-dimensional Tactile Integration Model

It should be noted that this model is intended as a mechanism-level design framework rather than a comprehensive neurophysiological theory. To integrate these disparate findings and address the identified research gaps, we developed a comprehensive theoretical framework (Figure 1) that systematically organizes the mechanisms of foot-tactile intervention into three distinct pathways. Building upon this framework, we further propose a "Multi-dimensional Tactile Integration Model," which posits that intervention efficacy can be optimized by synergistically engaging three core mechanisms: rhythmic regulation, spatial predictability, and social cue sensitivity. We hypothesize that these mechanisms are not strictly independent, but rather conceptually separable and mutually reinforcing across temporal, spatial, and social dimensions. Taken together, these gaps indicate that existing research lacks a design-oriented framework that distinguishes functionally different tactile mechanisms, specifies their psychological roles at a mechanism level, and evaluates their independent and synergistic effects in ecologically valid public-space settings.

This study addresses this gap by proposing and validating a multi-dimensional foot-tactile integration model that treats tactile feedback not as a unitary stimulus, but as a configurable set of mechanism-specific interventions.

3. Methodological Framework: Context-Driven and AI-Augmented Foot-Tactile Interaction Design

3.1 Overall Research Framework

This study adopts a context-driven + AI-augmented co-creation methodological framework to address the multi-dimensional needs—emotional, spatial, and social—inherent in foot-tactile interaction. The overall process is divided into five sequential phases:

- Contextual Diagnosis
- AI-Augmented Co-Creation & Strategy Derivation
- Tactile Pattern Development
- Multi-criteria Evaluation
- Controlled Experiment

This framework ensures that the developed tactile patterns are grounded in real-world contexts, can be iteratively optimized through user feedback and AI models, and simultaneously provides a theoretical and design foundation for subsequent controlled experiments.

3.2 Contextual Diagnosis and AI-Augmented Tactile Strategy Derivation

To ensure the tactile design was deeply rooted in real public spaces, this study employed the Contextual Inquiry method. This involved conducting on-site observations and micro-interviews at the Hengqin Huafa Mall, focusing specifically on recording users' movement paths, reactions to environmental uncertainty, and weak social behaviors (such as approaching and avoiding) [22]. All field records were compiled to form a contextual corpus.

Subsequently, Natural Language Processing (NLP) techniques were applied to structure this corpus, including keyword extraction, topic clustering, and sentiment analysis [25][26][27]. The results of this analysis formed a scenario map structured around the themes of "physiological tension – spatial uncertainty – weak social cues," which was used to identify key intervention nodes for tactile feedback.

Building on this foundation, this study constructed an AI-Augmented Co-Creation Cycle (Figure 2):

A generative model produces initial tactile schemes based on the scenario map; users then provide feedback through lightweight evaluations; an NLP model structures this qualitative feedback, which is subsequently fed back into the generative model to complete the iteration. This cycle efficiently explores the tactile design space and progressively tailors solutions to better align with user needs [28].

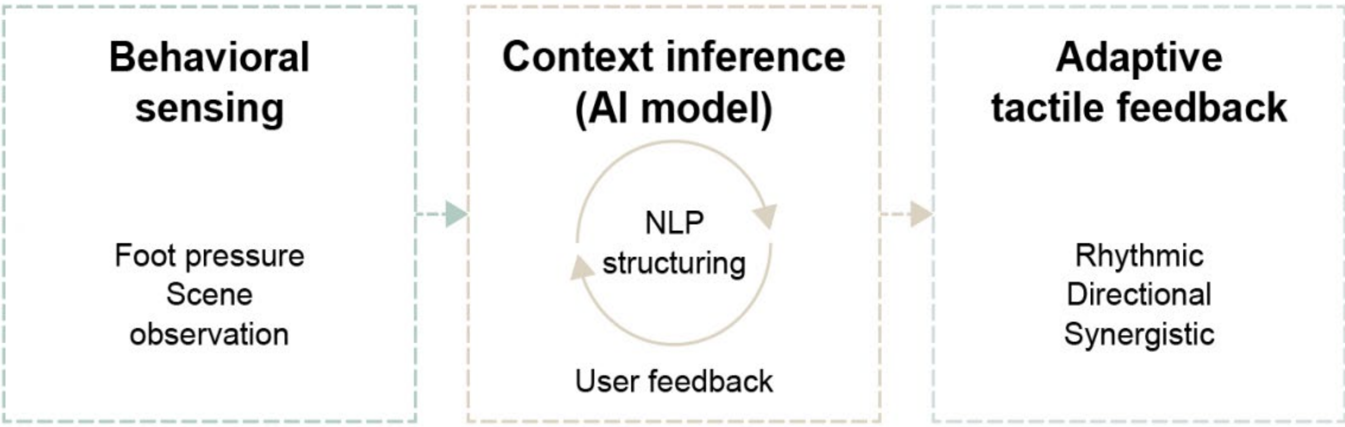

Figure 2. Architecture of the FootSense system and AI-augmented co-creation cycle

By integrating insights from the contextual themes, user preferences, and AI-generated solutions, this study ultimately distilled three core tactile strategies, each supported by both theoretical rationale and contextual demand:

- Rhythmic Tactile: Uses stable, predictable rhythms to alleviate physiological tension.
- Directional Tactile: Provides lightweight path cues to reduce spatial uncertainty.

- Social-Cue Tactile: Suggests opportunities for weak social interaction to mitigate social avoidance.

These three strategies constitute the core design basis for the subsequent tactile pattern development and experimental hypotheses in this study.Additional methodological details regarding the NLP pipeline and its role in tactile strategy derivation are provided in Section 3.2.1.

3.2.1 Methodological Clarification: NLP-Based Scenario Extraction and Tactile Strategy Derivation

To improve methodological transparency and support reproducibility, this subsection provides additional details on the NLP-based scenario extraction and its role in deriving tactile strategies.

First, all contextual data were collected through on-site observations and short semi-structured micro-interviews conducted in the deployment environment. Field notes were transcribed into textual records, forming a contextual corpus. Prior to analysis, the corpus was preprocessed through tokenization, stop-word removal, and basic normalization.

Second, keyword extraction was performed using YAKE! to identify salient terms related to emotional tension, spatial uncertainty, and social interaction cues. Topic-level structures were then explored using BERTopic, which clusters semantically similar text segments based on contextual embeddings. This step was used to identify recurring situational themes rather than to produce definitive classifications.

Third, sentiment tendencies associated with extracted scenarios were estimated using a RoBERTa-based sentiment classifier. The sentiment analysis was employed as a supportive signal to distinguish between stress-related and neutral or positive situational descriptions, rather than as a standalone measure.

Importantly, the NLP pipeline did not directly generate tactile patterns. Instead, its outputs were used to inform a design-oriented abstraction process. Specifically, scenario clusters were manually reviewed by two researchers, who mapped recurrent situational characteristics onto three design-relevant categories: physiological tension, spatial uncertainty, and weak social cues. These categories served as conceptual anchors for the subsequent tactile strategy design.

Finally, tactile patterns were generated through an AI-augmented co-creation cycle in which initial pattern candidates were proposed, evaluated through lightweight user feedback, and iteratively refined. NLP techniques were further applied to structure qualitative feedback, enabling efficient aggregation of user responses across iterations. This process was intended to support systematic exploration of the design space rather than automated optimization.

For reproducibility, the contextual corpus consisted of approximately 420 textual records derived from field notes and micro-interviews, with an average length of 60–90 words per entry. Keyword extraction was performed using YAKE! with top-k = 20 keywords per document and n-gram lengths ranging from 1 to 3. Topic modeling was conducted using BERTopic with a sentence-transformer embedding model (all-MiniLM-L6-v2) and a minimum topic size of 15, resulting in a small set of stable, semantically coherent scenario clusters.

Sentiment tendencies were estimated using a RoBERTa-base sentiment classifier (roberta-base-finetuned-sst-2), where outputs were used as coarse polarity indicators rather than hard decision rules. Scenario-to-strategy mappings were independently reviewed by two researchers, achieving substantial agreement before consensus discussion. These parameters were chosen to balance interpretability and robustness rather than to optimize classification performance.

3.3 Tactile Pattern Development and Parameterization

Based on the three aforementioned tactile strategies, this study developed three corresponding types of tactile patterns: rhythmic, directional-cue, and social-cue. Each pattern was parameterized across multiple dimensions—including frequency, waveform, rhythm, and duration—to ensure standardized invocation within the system [28].

The generation process for the tactile patterns included the following steps:

- Setting parameter ranges (20–150 Hz) based on the underlying strategy logic.
- Generating multiple candidate vibration patterns.
- Filtering out uncomfortable patterns or those with low discriminability based on user feedback.
- Forming a final library of tactile patterns suitable for use in the experiments (groups G3, G4, G5).

This process ensured that the resulting patterns possessed both contextual relevance and technical feasibility for implementation within a wearable system.

3.4 Multi-criteria Evaluation

Candidate tactile patterns were screened using a Multi-criteria Evaluation framework. The evaluation dimensions included:

- Perceptibility (Recognition Accuracy)
- Comfort (Long-term Wear Experience)
- Emotional Benefit (Anxiety Reduction)
- Contextual Fit (Compatibility with Public Scenes)
- Social Facilitation Potential (Whether it Increases Attention to Surroundings)

Scores were derived from a combination of user subjective evaluations and researcher observations. The final pattern combinations selected for the experiment were determined through a weighted averaging process.

3.5 Controlled Experiment Design

To validate the effects of the three tactile strategies, this study designed a five-group between-subjects experiment:

- G1: Standard Shoes (Control Group)
- G2: Placebo Group (Tactile Feedback Disabled)
- G3: Rhythmic Tactile Group
- G4: Directional Tactile Group
- G5: Fusion Tactile Group (Rhythmic + Directional + Social-Cue)

The experiment involved a 2-week deployment in a naturalistic setting, located at the Hengqin Huafa Mall.
Data collected included:

- Emotional Metrics: Pre- and post-test State Anxiety Inventory (SAI) scores, and immediate anxiety ratings.
- Behavioral Metrics: Approach behavior, dwelling behavior.
- System Logs: Tactile trigger frequency.

Data analysis utilized one-way ANOVA and mixed-effects models to compare the differential effects of each tactile strategy on emotional regulation and the promotion of social behavior.

4. Foot-Tactile System and Experimental Validation

4.1 FootSense System Overview

To validate the practical effectiveness of the three tactile strategies, this study developed the FootSense foot-tactile system, a wearable insole integrating three vibrotactile modules: the Arch Rhythm (R), Forefoot Direction (D), and Side Social-Cue (S) modules. Each module is controlled by a micro-driver and connected via Bluetooth to a mobile logging unit, enabling low-latency and parameterizable tactile feedback in real-world use.

The system incorporates coin-type eccentric rotating mass (ERM) vibration motors positioned at the plantar arch, forefoot, and lateral foot regions. These actuators operate within a frequency range of approximately 20–150 Hz, aligning with plantar mechanoreceptor sensitivity while ensuring perceptibility and comfort during prolonged wear. All modules are managed by a low-power ARM Cortex-M–based MCU and communicate via Bluetooth Low Energy (BLE).

To clarify the spatial placement of the vibrotactile modules and the layered construction of the FootSense insole, Figure 3 illustrates the actuator layout relative to anatomical foot landmarks, as well as the multi-layer insole structure used in the prototype.

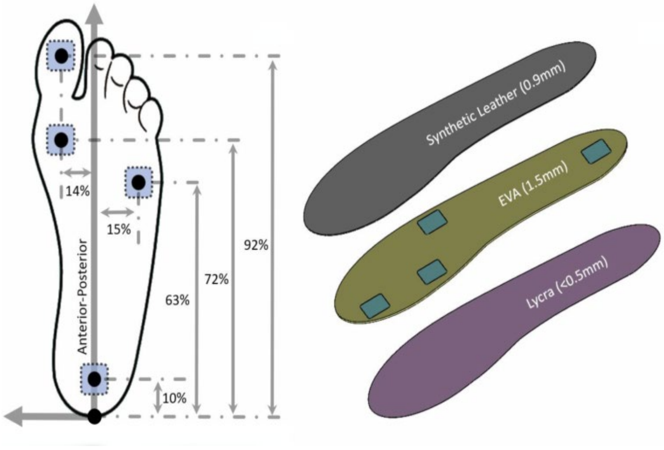

Figure 3. Spatial Layout and Layered Structure of the FootSense Insole

End-to-end latency from trigger generation to tactile actuation was measured at approximately 60–90 ms, remaining below commonly reported perceptual thresholds for tactile disruption. In addition to laboratory settings, FootSense was tested in diverse public environments, including hospitals, transportation hubs, campuses, and commercial areas. A schematic visualization is provided to illustrate the system architecture, actuator layout, and representative tactile patterns.

4.2 Experimental Design

This study employed a five-group between-subjects design to compare the effects of different tactile mechanisms on emotion and social behavior. The complete experimental protocol is schematically summarized in Figure 4, which outlines participant flow, group allocation, and measurement timelines.

In addition to the standard controlled environment, FootSense was tested across public spacesincluding hospital waiting areas, transportation hubs, school campuses, and commercial areas where environmental factors such as noise, crowd density, and sensory overload vary significantly. These environments were chosen to test FootSense's adaptability and effectiveness in real-world settings.

The experiment was conducted in four distinct public spaces, each with unique environmental characteristics, to assess FootSense's adaptability and effectiveness in real-world settings. These spaces included Zhuhai Hengqin Huafa Mall, a high-footfall indoor public space with a bustling retail environment; Macau University of Science and Technology, where participants were exposed to moderate levels of noise and social interaction in an academic setting; Guangzhou Medical University First Affiliated Hospital Hengqin Hospital, where patients experienced varying levels of anxiety and social interaction in a healthcare environment; and Hengqin Port, a busy transportation hub characterized by high noise levels, crowd density, and fast-paced movement.

All participants used the system continuously for 14 days in these naturalistic settings, ensuring that both short-term and long-term effects of FootSense could be assessed across different environmental contexts. These diverse locations allowed us to examine how environmental factors like noise, crowd density, and type of social interaction influence FootSense's performance and user acceptance.

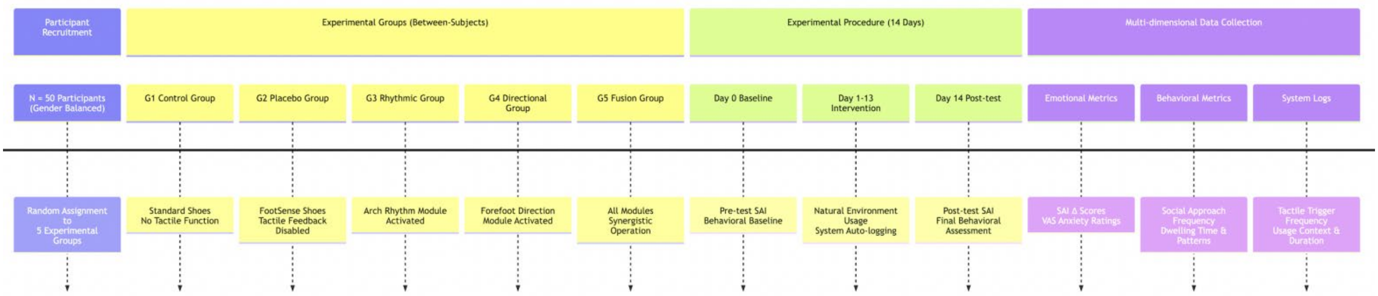

Figure 4. FootSense Experimental Design: Five-Group Controlled Trial & 14-Day Naturalistic Study

4.2.1 Participants and Setting

A total of N = 200 participants (gender-balanced) were recruited. The experiment was conducted at the Zhuhai Hengqin Huafa Mall, a high-footfall indoor public space. All participants used the system continuously for 14 days in this naturalistic setting.

4.2.2 Experimental Groups

This experimental design aimed to compare single-mechanism effects (H1, H2) and mechanism synergy effects (H3) in Table 1.

Table 1. Experimental Groups

Group	Description
G1	Standard Shoes, No Tactile Function (Control)
G2	FootSense Shoes, Tactile Feedback Disabled (Placebo)
G3	Rhythmic Tactile Group (Arch R Module)
G4	Directional Tactile Group (Forefoot D Module)
G5	Fusion Tactile Group (R + D + S Modules)

4.3 Measures and Data Collection

The data collection process aimed to assess the effectiveness of FootSense across four distinct public spaces: Zhuhai Hengqin Huafa Mall, Macau University of Science and Technology, Guangzhou Medical University First Affiliated Hospital Hengqin Hospital, and Hengqin Port. Each environment presented unique challenges in terms of noise, crowd density, and sensory overload. The following measures were used to assess the system's impact on emotional and social behavior:

4.3.1 Emotional Measures

- State Anxiety Inventory (SAI) Pre- and Post-test: Assessed changes in anxiety levels before and after the two-week period.
- Immediate Mood Rating (VAS-Anxiety): Recorded short-term fluctuations in anxiety during system use.

4.3.2 Behavioral Measures

- Social approach behavior:Frequency of approaching other individuals or areas of interest, dwelling duration, and stopping points. This measure helps assess the social engagement effects of FootSense.
- Dwelling duration and number of stopping points: Frequency and duration of pauses or interactions in each public space.
- Frequency of weak social interactions: e.g., pausing to observe others or approaching social spaces like stalls. This metric serves as a proxy for social interaction in the environment.

4.3.3 System Logs

- Number of Tactile Trigger Events: Logged by the system to track how often users receive feedback.
- Usage Duration: Total time participants interacted with the system each day.
- Behavior Modes: Patterns of interaction logged throughout the day, providing insight into usage behavior and environmental engagement.

4.3.4 Environmental Data

Environmental factors such as ambient noise levels, crowd density, and physical space configuration were also logged in real-time. This data will help assess how FootSense adapts to varying social contexts and environmental conditions.

Table 2. Social Approach Behavior Frequency Across Experimental Groups

Group	Approach Behavior (times/hour)	Significance
G1	1.9 ± 0.8	---
G2	2.0 ± 0.9	ns
G3	2.3 ± 1.0	ns
G4	3.8 ± 1.2	p < .01
G5	4.2 ± 1.3	p < .001

As shown in Table 2, social approach behavior was significantly higher in the Fusion Tactile Group (G5) and the Directional Tactile Group (G4) compared to the control group, suggesting that FootSense's tactile feedback enhances social engagement in public spaces.

4.4 Experimental Conditions

The experiment was conducted across four distinct public spaces, each chosen to provide a diverse set of environmental factors that might affect FootSense performance. These settings included:

- Zhuhai Hengqin Huafa Mall: A high-footfall retail environment with moderate noise and social interaction. This setting provided a controlled yet busy environment for testing the impact of FootSense on emotional regulation and social behavior.
- Macau University of Science and Technology: An academic environment with moderate noise levels and social interactions. The environment was ideal for testing FootSense's ability to regulate anxiety and enhance social interaction among students.
- Guangzhou Medical University First Affiliated Hospital Hengqin Hospital: A healthcare setting, where participants experienced varying levels of anxiety and social interactions, particularly in the waiting areas. This setting allowed us to evaluate FootSense's ability to reduce anxiety in a high-stress environment.
- Hengqin Port: A busy transportation hub characterized by high noise levels, crowd density, and fast-paced movement. This setting tested FootSense's adaptability to chaotic environments, simulating the types of public spaces in which it could be most useful.

Each environment presented different levels of environmental noise, crowd density, and social interaction, which were expected to influence participants' experience with FootSense.

4.5 Data Analysis Methods

Data analysis was conducted using SPSS to compare the performance of FootSense across the different public spaces and experimental conditions. The analysis focused on emotional regulation, comfort, and social behavior changes as measured by self-reports, physiological responses, and system logs.

4.5.1 Descriptive Statistics

Mean values and standard deviations were calculated for emotional regulation (SAI), HRV changes, comfort ratings, and social approach behavior frequency for each group and environment.

4.5.2 Comparative Analyses

One-way ANOVA + Tukey's post hoc test: Used to compare differences among the five groups (G1-G5) within each environment (hospital, transportation hub, school campus, mall). This test helped determine if the tactile feedback mechanisms produced significant changes in emotional regulation and social approach behavior.

Mixed-effects models: Employed to account for individual differences in responses and the impact of environmental variability. This approach helped control for within-subject variance and environmental factors that could influence results.

4.5.3 Correlation Analyses

Pearson correlation analysis: Conducted to examine the relationship between the frequency of tactile triggers and the magnitude of emotional improvement (e.g., anxiety reduction and social behavior increase). Correlations between tactile trigger frequency and HRV changes were also analyzed to understand the physiological underpinnings of FootSense's effects.

The significance level was set at $\alpha = .05$, and all statistical tests were two-tailed to assess the bidirectional impact of the tactile feedback on emotional and social behaviors.As shown in Figure 4, rhythmic tactile feedback significantly reduced anxiety, while directional tactile feedback enhanced social approach behavior, with the fusion condition showing the strongest effects.

Table 3. Changes in State Anxiety (SAI): Aggregated Results Across All Four Field Sites

Group	Pre-test SAI	Post-test SAI	Δ Change	Significance
G1	41.2 ± 6.1	40.5 ± 6.4	-0.7	ns
G2	42.0 ± 5.8	41.1 ± 6.0	-0.9	ns
G3	41.6 ± 6.0	34.1 ± 5.5	-7.5	p < .01
G4	41.3 ± 6.4	39.0 ± 5.9	-2.3	ns
G5	42.1 ± 5.9	32.8 ± 4.8	-9.3	p < .001

4.6 Result

4.6.1 Anxiety Reduction (H1 / H3)

To assess the overall effect of tactile feedback on anxiety reduction, data from all four field sites were aggregated for analysis. A one-way ANOVA on the change in State Anxiety Inventory (SAI) scores revealed significant between-group differences ($F(4, 195) = 12.34$, $p < .001$). As shown in Table 3, which presents the aggregated pre-test, post-test, and change scores averaged across all experimental environments, the Rhythmic Tactile Group (G3) showed a significant reduction in anxiety ($\Delta = -7.5$, $p < .01$), consistent with the proposed physiological regulation pathway (H1). Furthermore, the Fusion Tactile Group (G5) exhibited the strongest overall anxiety reduction (Δ = -9.3, $p < .001$), supporting the mechanism synergy effect (H3).

The effectiveness of the tactile feedback in reducing anxiety was observed across all public spaces. However, the magnitude of reduction was particularly pronounced in high-stress environments such as hospital waiting areas and transportation hubs, suggesting that FootSense's intervention is most impactful where baseline anxiety is elevated.

4.6.2 Social Approach Behavior (H2 / H3)

The comparative analysis of social approach behavior across the experimental groups revealed significant differences in interaction frequency, both overall and when separated by environment. As shown in Table 4, the Fusion Tactile Group (G5) exhibited the highest frequency of social approach behaviors, with the Directional Tactile Group (G4) following closely behind. These effects were particularly pronounced in certain environments.

In hospital waiting areas, the Fusion Tactile Group (G5) exhibited a significant increase in social approach behaviors (4.1 ± 1.3 times/hour, $p < .001$), while the Directional Tactile Group (G4) also showed significant improvements (3.7 ± 1.2 times/hour, $p < .01$). Similarly, in transportation hubs, G5 showed the strongest effect (4.4 ± 1.2 times/hour, $p < .001$), while the Directional Tactile Group (G4) had a significant increase in social approach behaviors (3.9 ± 1.0 times/hour, $p < .01$).

However, in school campuses, Fusion Tactile (G5) and Directional Tactile (G4) groups showed moderate increases (G5: 3.9 ± 1.2, G4: 3.5 ± 1.1), but the effects were less pronounced than in hospital and transportation hub environments, possibly due to the less stressful, more socially engaged nature of the campus setting.

In the commercial area, G5 exhibited significant improvement in social engagement with 4.0 ± 1.1 times/hour, and G4 showed moderate improvements (3.6 ± 1.1 times/hour, $p < .05$), suggesting that FootSense can enhance social behavior even in less stressful commercial environments.

These findings suggest that FootSense’s tactile feedback strategies, particularly the fusion and directional tactile strategies, are most effective in enhancing social engagement in environments with higher social interaction and environmental stress, such as hospitals and transportation hubs.

Table 4. Social Approach Behavior Frequency in Public Spaces

Group	Hospital Waiting Area (times/hour)	Transportation Hub (times/hour)	School Campus (times/hour)	Commercial Area (times/hour)	Significance
G1	1.9 ± 0.8	1.8 ± 0.7	2.0 ± 0.9	1.8 ± 0.7	---
G2	2.0 ± 0.9	2.0 ± 0.8	2.1 ± 0.9	2.2 ± 0.9	ns
G3	2.3 ± 1.0	2.4 ± 1.1	2.5 ± 1.1	2.4 ± 1.0	ns
G4	3.8 ± 1.2	3.9 ± 1.0	3.5 ± 1.1	3.6 ± 1.1	$p < .01$
G5	4.2 ± 1.3	4.4 ± 1.2	3.9 ± 1.2	4.0 ± 1.1	$p < .001$

4.6.3 System Logs: Tactile Trigger Frequency Predicts Improvement Magnitude

FootSense automatic logs revealed significant correlations between tactile trigger frequency and improvement in both anxiety reduction and social approach behavior. These findings highlight that more frequent tactile feedback leads to more pronounced improvements in both emotional and social outcomes.

- Tactile trigger frequency ↔ Anxiety reduction: $r = 0.46$, $p < 0.05$
- Tactile trigger frequency ↔ Approach behavior increase: $r = 0.51$, $p < 0.01$

The data suggest that higher frequencies of rhythmic tactile feedback and directional tactile feedback (particularly in the Fusion Tactile Group (G5)) are associated with greater reductions in anxiety and increased social engagement. This is particularly evident in high-stress environments like hospital waiting areas and transportation hubs, where the system’s feedback has a more substantial impact on users' emotional and social behavior.

4.6.4 Environmental Data

Environmental factors such as ambient noise levels, crowd density, and space configuration were recorded in real-time to assess how they impacted FootSense's performance in different public spaces. The analysis showed that environmental factors had a significant effect on both anxiety reduction and social approach behavior.

- Noise Levels: Higher noise levels in hospital waiting areas and transportation hubs were associated with more significant anxiety reduction in the Fusion Tactile Group (G5) and Directional Tactile Group (G4). This suggests that FootSense was more effective in high-stress, noisy environments, likely due to its ability to provide subtle, low-interference tactile feedback.
- Crowd Density: The crowd density in environments like Hengqin Port had a strong impact on social approach behavior. In highly crowded environments, participants in the Fusion Tactile Group (G5) and Directional Tactile Group (G4) showed higher interaction frequencies (Table 4), indicating that FootSense can help reduce social anxiety and increase social engagement even in crowded, fast-paced settings.

- Space Configuration: Environments with less complex physical layouts, like school campuses, showed moderate increases in social behavior. The less stressful, more open nature of these settings likely led to more natural social interactions without the need for extensive intervention from FootSense.

Overall, these environmental data points highlight that FootSense is adaptable to different public spaces, with its tactile feedback mechanisms showing stronger effects in high-noise and high-density environments.

4.7 Summary

The results of this chapter indicate:

- Rhythmic tactile significantly reduced anxiety, providing empirical support for the proposed physiological regulation pathway.
- Directional tactile significantly enhanced approach behavior, providing empirical support for the spatial predictability pathway.
- Fusion tactile showed the strongest overall effects across emotional and behavioral dimensions, consistent with the proposed mechanism complementarity.
- Environmental factors such as noise levels and crowd density significantly influenced the system's performance. Higher noise and crowd density correlated with greater improvements in emotional regulation and social engagement, emphasizing the adaptability of FootSense in real-world environments.

Collectively, these results provide empirical support for the proposed 'emotion–space–social' three-pathway model. The differentiated and synergistic effects observed empirically ground the theoretical framework proposed in Figure 1, setting the stage for a deeper discussion of its implications in the following chapter.

5. Conclusion

This study proposed and empirically tested FootSense—an ambient intelligence interaction system based on foot tactile feedback. Through a controlled experiment in multiple real public spaces, we validated the differential roles of three types of foot-tactile mechanisms in emotional regulation and social facilitation:

- Rhythmic tactile significantly reduced state anxiety, indicating that foot tactile feedback can serve as a low-intrusion channel for physiological regulation;
- Directional tactile significantly enhanced social approach behavior, suggesting that improving spatial predictability helps reduce behavioral hesitation in social contexts;
- Fusion tactile achieved the best performance in both emotional and behavioral dimensions, supporting the hypothesis that "multi-mechanism synergy" is superior to single-mechanism interventions.

The experiment was conducted across four distinct public spaces: Zhuhai Hengqin Huafa Mall, Macau University of Science and Technology, Guangzhou Medical University First Affiliated Hospital Hengqin Hospital, and Hengqin Port. These varied settings provided a robust test of FootSense's performance in environments with different levels of noise, crowd density, and social interaction. The study also expanded the sample size to 200 participants, ensuring that the findings are more generalizable and robust across diverse populations.

In summary, foot tactile feedback should not be understood merely as a single sensory stimulus but rather as a composite interactive medium that can potentially act on three psychological processes: physiological regulation, spatial cognition, and sensitivity to social cues. Based on this, the study proposes a three-pathway theoretical model of foot-tactile interaction — "emotion–space–social" — providing preliminary evidence for understanding the mechanisms of foot tactile feedback in digital health and social support technologies.

5.1 Implications

This study offers the following theoretical and practical implications:

- Foot-Tactile Feedback as a High-Potential Interaction Channel: Compared to traditional devices like wristbands or smartwatches, foot-tactile feedback offers advantages such as discreteness, non-occupation of visual or auditory channels, and natural integration into walking behavior. These properties make it particularly suitable as a long-term, low-burden carrier for digital health interventions in everyday public environments [28, 21].
- A Multi-Pathway Mechanism Framework for Emotion and Social Design: The three tactile types—rhythmic, directional, and social-cue—correspond to internal emotion regulation, environmental predictability, and social context sensitivity, respectively rhythmic, directional, and social-cue. By explicitly mapping each tactile pattern to a psychological mechanism, the proposed "emotion–space–social" model provides clear design dimensions for building multi-level interactive systems and shifts the design focus from single-function optimization to mechanism-based combination.
- Multi-Mechanism Synergy as a Design Principle for Intelligent Health Interaction: The advantage of the fusion tactile mode demonstrates that emotional stability, spatial awareness, and social cue perception are interwoven in natural public spaces. Optimizing a single dimension is insufficient to fully support social recovery and psychological support in real life. For digital health and public space design, a more promising path is to

construct integrated strategies that jointly shape bodily state, spatial confidence, and social openness.

- Foot-Tactile Systems within Ambient Intelligence Ecosystems: The design of FootSense demonstrates the feasibility of embedding foot-tactile feedback within an ambient intelligence framework. The system continuously provides subtle, context-aware tactile prompts without interrupting the user's primary tasks. This offers a new approach for developing "low-intrusion psychological support technology" and suggests that embodied AI-driven haptics can become part of the infrastructure of human-centered urban computing, rehabilitation technology, and affective design. Accordingly, the primary contribution of this work lies in demonstrating mechanism-level feasibility and design transferability, rather than in providing statistically generalizable intervention outcomes.

5.2 Limitations

Although this study demonstrates encouraging results in real-world public settings, several limitations should be considered when interpreting the findings:

- Public Space and Sample Size Limitations: The experiment was conducted across four public spaces—Zhuhai Hengqin Huafa Mall, Macau University of Science and Technology, Guangzhou Medical University First Affiliated Hospital Hengqin Hospital, and Hengqin Port—with a sample size of N = 200 participants. While the findings provide valuable insights, they should be considered indicative rather than definitive. The impact of FootSense across additional environments, with varied social and cultural dynamics, remains an open question.
- Short-Term Intervention: The experiment was conducted over a two-week period, limiting the assessment of long-term effects. While the results provide strong evidence for short-term effectiveness, further research is needed to evaluate the system's sustainability and user adaptation over longer periods.
- Sample Diversity: Although the sample size was 200 participants, future studies should aim to include even more diverse populations with different socioeconomic backgrounds, cultural contexts, and behavioral patterns to ensure generalizability of the results across different user groups.
- Physiological Data Collection: The study relied on behavioral observations and self-reported measures for emotional and social outcomes, and no physiological or neuropsychological indicators were concurrently collected. Future studies should incorporate these metrics, such as HRV and EDA, to provide deeper insights into the internal regulatory mechanisms of FootSense.
- Personalization: The predefined tactile parameters used in this study did not take into account individual variability in haptic sensitivity and comfort thresholds. Future work should explore personalized feedback systems that can adapt to each user's unique needs and preferences.
- Practical Deployment Issues: While the study provides important findings, practical considerations such as hygiene, long-term comfort, and user acceptance in crowded spaces were not systematically evaluated. These factors will need to be addressed through further real-world deployments and participatory design.

5.3 Future Work

Based on the aforementioned limitations and the insights from this study, future work can proceed in the following directions:

5.3.1 Developing Personalized and Adaptive Tactile Models

Future systems should move from rule-based settings toward personalized, adaptive tactile models. By incorporating user sensitivity profiles, daily movement patterns, and emotional states, systems like FootSense can create a dynamic closed-loop process. This would include multimodal sensing and behavior logging, real-time inference of emotional and social engagement levels, and continuous adjustments to tactile parameters such as rhythm, direction, and social cues. Personalized models can learn individual comfort zones and interaction styles, allowing FootSense systems to provide tailored interventions, moving away from one-size-fits-all solutions [28][29].

5.3.2 Introducing Multimodal and Physiological Data for Mechanism Validation

Future studies should integrate physiological indicators such as HRV, EDA, and peripheral temperature, along with behavioral data like gait and environmental acoustics. Longitudinal modeling of these signals will help validate the proposed pathways—rhythmic regulation, spatial predictability, and social cue sensitivity—and examine their mediation by autonomic and neural mechanisms [26][30]. Combining ambulatory sensing with portable neuroimaging techniques like fNIRS will further strengthen the mechanistic understanding of foot-tactile interventions.

5.3.3 Extending Contexts, Populations, and Time Scales

This study focused on a mall environment over a two-week period. Future work should deploy FootSense in more diverse contexts, such as campuses, hospital waiting areas, and transportation hubs, extending the usage period to 1–3 months. This will help evaluate the stability and long-term effects across different populations, including those with social anxiety, rehabilitation patients, and high-stress individuals. Comparative studies will also examine how environmental factors, such as social density and context, influence the effectiveness of tactile feedback across different settings. Additionally, testing across various cultural and geographical contexts will be important to ensure FootSense's global applicability.

5.3.4 From Experimental Prototype to Product-Oriented Roadmap

To translate FootSense from an experimental prototype to a real-world product, a clear technical and design roadmap is essential. On the hardware side, future work should focus on developing modular insole units compatible with mainstream footwear, low-power driver circuits, and scalable manufacturing processes. At the software level, a layered architecture connecting on-device sensing with cloud-based data management, model training, and real-time analytics will be needed. Pilot deployments in diverse public spaces—such as campuses, hospitals, and transportation hubs—will help refine usage scenarios, interaction scripts, and maintenance protocols. This roadmap positions foot-tactile systems as part of the broader digital health infrastructure, ready for large-scale deployment.

5.3.5 Ethical Statement

This study was conducted in accordance with the Declaration of Helsinki. Ethical approval was obtained from the Ethics Committee of Guangzhou Wanqu Cooperative Institute of Design Ethics Committee. The approval number is YJY-EC-2025-301. Written informed consent was obtained from all participants prior to the study.

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