Smart Insole Visual Foot Pressure Feedback in Mixed Reality Environments: Impact on Gait, Heart Rate, Workload, and Engagement in Treadmill Walking

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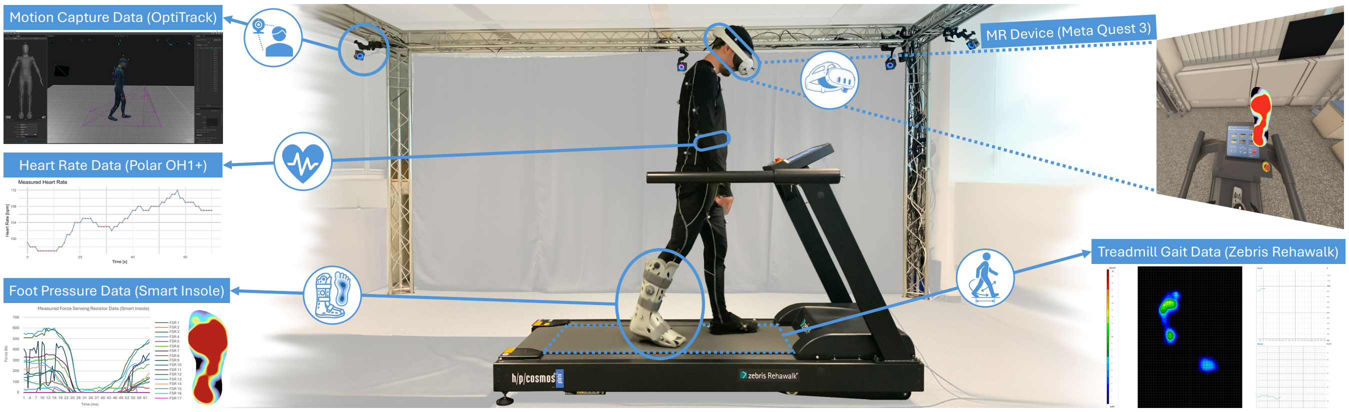

Figure 1: Study setup of a participant walking on an instrumented treadmill wearing an orthosis with a prototyped smart insole, including real-time plantar pressure visualization in virtual/mixed reality, full-body motion capture, and heart rate monitoring.

Abstract

Although orthotic footwear supports the rehabilitation of lower-limb injuries, it often impairs natural gait control. Due to the lack of additional feedback, patients are unaware of abnormal foot pressure distributions, which can hinder recovery. Prior work has demonstrated the potential of virtual and mixed reality (VR/MR) for gait training with visual feedback. However, it remains unclear how smart insole pressure feedback affects gait and user experience in VR/MR. We conducted a within-subject study with 24 participants, testing four visual feedback modalities across three virtual environments during treadmill walking. Quantitative and qualitative results showed that a virtual forest altered gait, increased engagement, and reduced workload, while a pressure heatmap influenced objective and subjective measures depending on the environment. We provide empirical insights on foot augmentation in immersive settings and contribute design recommendations for future VR/MR gait training applications.

CCS Concepts

• **Human-centered computing** → **Human computer interaction (HCI)**; **Empirical studies in HCI**; **Virtual reality**; **Mixed / augmented reality**.

Keywords

Foot Augmentation, Smart Insoles, Gait Analysis, Virtual Reality, Mixed Reality, Visual Feedback

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1 Introduction and Background

Orthopedic footwear, such as a controlled ankle motion boot, is essential for stabilizing lower-limb injuries but substantially alters gait, making walking harder to control [23, 36]. Patients often need to adjust their gait or reduce plantar pressure, but without guidance this is difficult, potentially slowing rehabilitation, prolonging recovery, or causing persistent impairments [22]. Critically, patients rarely receive direct feedback about pressure distribution or gait within the orthosis, which limits self-correction. Conventional treadmill training in laboratories relies on expert supervision or provides only basic cues, often insufficient for gait adaptation, balance, and pressure control [7]. Consequently, this expert-dependent approach restricts patient-device interaction and access to relevant gait information [35].

Therefore, visual and interactive feedback offers potential, enabling users to actively adjust gait and increase independence [31]. For example, sensorized footwear, such as pressure-sensitive insoles, has been used in standard shoes to provide real-time feedback for posture exercises using Center of Pressure (CoP) feedback [4, 5, 13]. Building on their use in lower-limb exercises, pressure-sensing insoles have been integrated as real-time input devices in virtual reality (VR), supporting gait detection and locomotion, such as perceiving ground surfaces while walking [32, 33]. These systems show that visual foot augmentation can guide mobility, balance, and foot placement while supporting task performance. Although solutions for gait-modifying orthoses are lacking, implementing the sensorized concept in interactive training could enable feedback-driven gait adaptation, even when the device substantially alters walking patterns.

In this context, VR and mixed reality (MR) enhance this approach by embedding visual feedback into immersive training scenarios [7, 14, 24, 27]. Compared to screen-based feedback, head-mounted display (HMD)-based VR provides a reliable tool for treadmill training [38], enabling flexible applications beyond stationary labs and supporting gamified training that can influence motivation and physiological responses [3, 6, 10, 20, 37]. While conventional training is usually limited to laboratory settings, some VR studies have used virtual replicas of the same room to improve comparability and generalization [11]. However, immersive VR can increase task-dependent cognitive load [25], which should be managed to preserve training benefits. Beyond traditional laboratory setups, naturalistic virtual environments have shown potential to support stress recovery in other contexts [34], suggesting opportunities for future gait training scenarios.

Despite these advances, most prior work has examined visual feedback or environmental factors in other application domains and typically relies on standardized footwear. It remains unclear how immersive settings and visual pressure augmentation affect movement patterns, physiological responses, and user experience in gait-modifying footwear. To address this gap, our research question asks how smart insole feedback and immersive contexts influence objective gait measures, heart rate, and subjective workload and engagement during treadmill walking. Therefore, we developed a sensorized foot orthosis and conducted a study with healthy participants to investigate the mechanisms of feedback-driven gait modulation under controlled conditions, serving as a basis for future virtual training developments.

In this paper, we present the results of an experimental user study with 24 participants investigating gait adaptation in VR/MR. Our work extends previous findings by focusing on gait-modifying orthopedic footwear, which presents unique challenges for adaptation. We show how foot pressure augmentation interacts with immersive contexts and how naturalistic and stationary VR/MR settings with multiple feedback modalities affect gait, physiological responses, and user experience. Furthermore, we derive design implications for future immersive gait training applications.

2 Method

We conducted a mixed-method experimental user study to investigate the effects of foot pressure visualization and environmental factors on gait, heart rate, workload, and user engagement during treadmill walking in VR/MR. To address this, the study followed a 4 × 3 within-subjects design with two independent variables: VISUALIZATION (four levels: *None*, *Heatmap*, *CoP*, *Histogram*) and ENVIRONMENT (three levels: *VR Forest*, *VR Lab*, *MR Lab*). Twelve experimental conditions were counterbalanced using a balanced Latin square to minimize order effects [1, 30], with each condition appearing equally often across 24 participants.

Quantitative measures included gait (spatial, temporal, and kinetic parameters) and heart rate, while subjective assessments captured workload and engagement. Semi-structured interviews provided qualitative insights, enabling deeper understanding to support the quantitative findings.

2.1 Stimuli

The stimuli for each condition are shown in Figure 2. The *VR Forest* environment, developed in Unity using Asset Store assets, features a straight forest path without audio to minimize distraction. Participant motion was matched to treadmill speed. The *VR Lab* replicates the physical lab, with a virtual treadmill synchronized to the real one. The *MR Lab* used Meta Quest 3 passthrough to show the real lab with a virtual pressure-feedback canvas. Three visualizations of plantar pressure were created (*Heatmap*, *CoP*, and *Histogram*), see Appendix A (Figure 4b). The *None* condition served as a baseline, while the other three used data from 17 force sensing resistors (FSRs) on the smart insole and were displayed at eye level for consistent visibility. **Heatmap:** Based on prior work [15, 26, 39], we developed a 2D plantar pressure heatmap using the prototype insole layout, mapping 17 FSRs to colors with Google's Turbo colormap [18], normalized to body weight. **CoP:** Following Elvitigala et al. [4, 5], a 1D colored bar was developed with a moving line indicated averaged pressure across forefoot, midfoot, and hindfoot zones. **Histogram:** A 2D *histogram* was developed to display cumulative pressure per foot zone using 20 area-scaled bars, while a virtual orthosis visualized real-time foot rotation.

2.2 Apparatus

The laboratory setup is shown in Figure 1. We developed a smart insole, placed inside an ankle motion boot orthosis, following Resch et al. [26], equipped with 17 FSR-400 sensors (5.6 mm diameter, 0.3 mm thick, 20 N range). A custom printed circuit board (PCB)

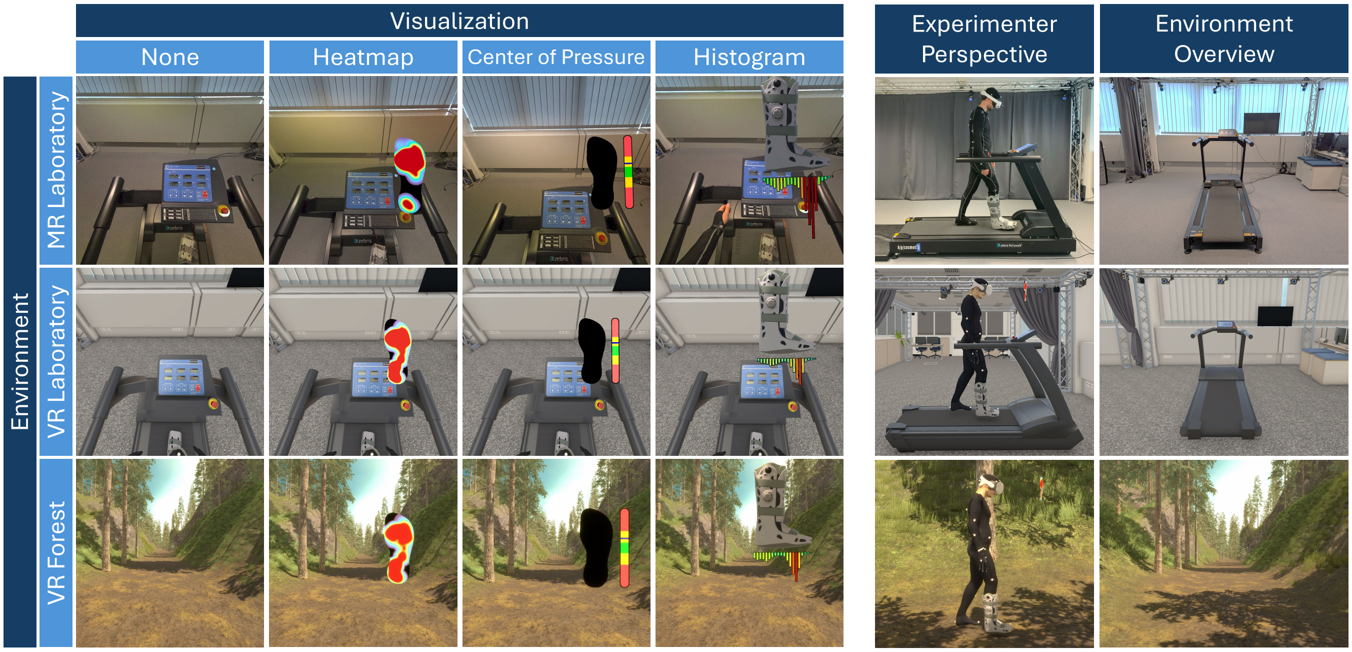

Figure 2: Participant perspective (left) and experimenter view (right) of the visualizations and environments.

with an ESP32 microcontroller streamed sensor data via MQTT at 100 Hz. An image of the prototype system is shown in Appendix A (Figure 4a). Virtual environments and visualizations were developed in Unity (v. 6000.0.46f1) using the Meta XR All-in-One SDK (v. 72.0.0) [17]. Two Mixamo avatars were used to ensure gender representation: the male "Passive Marker Man" and the female "Jody," with textures adapted to the motion capture system (MoCap) suit. A Meta Quest 3 with Elite Strap served as the HMD for VR and MR. An OptiTrack MoCap system with ten Prime^X 13W cameras captured skeleton data at 240 Hz (1280 × 1024 px). The system was calibrated per OptiTrack specifications (mean ray error 1.18 mm, wand error 0.25 mm). The "Baseline" template with 41 markers animated the virtual avatar in Motive software (v. 3.1.4). Heart rate was recorded using a Polar OH1+ optical sensor, validated for measuring physical activity [9]. Gait data were recorded at 100 Hz on a Zebris RehaWalk, FDM-THPL-S-2i, instrumented treadmill (3,120 capacitive sensors, 101.6 × 49.5 cm) using Zebris DM software (v. 2.0.4). All applications ran on a Windows 10 Pro PC with AMD Ryzen 5900X, GeForce RTX 3070, and 32 GB RAM.

2.3 Procedure and Tasks

The study was conducted under controlled laboratory conditions. After providing informed consent, participants completed a questionnaire on demographics, gait conditions, and VR/MR experience. Following this, the pulse sensor was attached to the forearm and verified for data transmission. Participants were then equipped with the MoCap suit and the sensorized orthosis, consistently worn on the right foot, and markers were placed according to the template. A T-pose was used to calibrate the skeleton. Participants were positioned on the treadmill with safety equipment, received the HMD, and the visualizations were aligned to eye level, avatar height scaled, and pressure data normalized to body weight. They were instructed to walk naturally while aiming to control their gait based on the visual feedback, maintaining balanced weight distribution and reducing localized pressure. Treadmill speed was set to 1.5km/h. Five gait trials of ten seconds each were recorded per condition, always starting with right-foot contact. After each condition, participants completed NASA Raw Task Load Index (RTLX) and User Engagement Scale - Short Form (UES-SF) questionnaires in VR [29], followed by a semi-structured interview for qualitative feedback. This procedure was repeated for all conditions. After the study, participants removed the HMD and tracking suit, were debriefed, and provided post-study feedback.

2.4 Measures and Data Analysis

Spatial, temporal, and kinetic gait parameters were recorded using the instrumented Zebris treadmill, appropriate for clinical gait analysis [12]. Spatial and temporal metrics included step/cycle characteristics, cadence, contact time, and stance/swing phases, while kinetics comprised maximum plantar pressure for hind-, mid-, and forefoot (all in cm,°, s, steps/min, N/cm²). Heart rate served as a secondary physiological control, reflecting general arousal during treadmill walking, and was recorded continuously in beats per minute (bpm) and aggregated per condition. Two subjective questionnaires were used after each condition. In this study, workload referred to the cognitive demand of processing visual pressure feedback while controlling gait, and was assessed with the NASA RTLX [8], commonly used in HCI. Participants rated six subscales per condition, and overall as well as subscale scores were analyzed. User engagement was measured using the UES-SF [21], with scores derived per subscale and overall. In a debriefing session, participants rated preferred and least liked conditions and provided final feedback. Quantitative data were analyzed using descriptive and inferential statistics, including two-way repeated measures (RM) Analysis of Variance (ANOVA).

Qualitative feedback was collected via semi-structured post-condition interviews, focusing on participants' experience, gait influence, and perceived pros and cons of the visualizations. Interviews were audio-recorded, transcribed using Buzz (Whisper large-v3), and manually verified. An inductive thematic analysis [2] was conducted to identify patterns across categories, with iterative coding cross-checked by a second researcher to ensure reliability and accuracy.

2.5 Participants

In total, 24 participants (14 male, 10 female) were recruited via institutional mailing lists. The age of participants was between 21 and 34 ($M = 27.54$, $SD = 2.55$). Six participants wore glasses during the study. Participants' familiarity with VR/MR was moderate (5-point Likert, $M = 2.5$, $SD = 1.1$). All participants were healthy, free of balance disorders or pain, and had right-leg or bilateral dominance to ensure consistent use of the right-foot orthosis. Foot dominance was assessed by participants' preferred kicking leg and a short single-leg stance test. Previous work indicates that leg dominance does not affect stance or balance in healthy young adults [19, 28].

The study followed institutional data privacy and hygiene protocols and received ethical approval by the German Society for Nursing Science (No. 23-027). All participants completed the study without interruption and were included in the analysis.

3 Results

3.1 Quantitative Results

3.1.1 *Gait Data.*

Gait parameters were analyzed using RM ANOVA (Greenhouse–Geisser for normal, aligned rank transform (ART) for non-normal data), revealing main effects of *Environment* and interactions across metrics.

Spatial: Path length was higher in *VR Forest* vs. *MR Lab* ($p < .004$). Gait cycle length and step width showed significant *Visualization × Environment* interactions in *VR Lab* (Heatmap, $p = .002$–$.014$), while foot rotation differed for the right foot in *VR Forest* ($p = .023$).

Temporal: *VR Forest* reduced cadence ($p = .030$) and increased cycle/contact times ($p = .001$–$.004$) vs. both labs. In *VR Lab*, Heatmap increased cadence and reduced cycle, swing, and stance times ($p = .001$–$.046$).

Kinetic: Heel, mid-, and forefoot pressures were higher in *VR Forest* (all $p \leq .008$), with *VR Lab* interactions driven by Histogram (increased forces) and partly reversed in Heatmap.

The main results are displayed as plots in Figure 3.

3.1.2 *Heart Rate.*

Heart rate data violated normality (Shapiro-Wilk, $p < .05$). An ART RM ANOVA revealed a main effect of *Environment* ($F(2, 253) = 4.43$, $p = .013$), but no effect of *Visualization* ($F(3, 253) = 1.01$, $p = .389$) nor interaction ($F(6, 253) = 0.53$, $p = .785$). Wilcoxon signed-rank tests with Holm correction showed higher heart rate in *VR Lab* vs. *VR Forest* ($p = .008$), while *MR Lab* vs. *VR Forest* ($p = .065$) and all other pairwise differences were not significant, see Figure 3.

3.1.3 *Workload.*

Overall NASA RTLX scores were normally distributed ($p > .069$) and showed no significant effects of VISUALIZATION ($F(2.23, 51.22) = 0.969$, $p = .394$, $\eta_p^2 = .040$), ENVIRONMENT ($F(2, 46) = 2.844$, $p = .068$, $\eta_p^2 = .110$), or their interaction ($F(3.96, 91.13) = 0.425$, $p = .789$, $\eta_p^2 = .018$), see Figure 3. Subscale analyses revealed effects for performance and frustration. Performance workload was lower in *VR Forest* than in *MR Lab* ($p = .002$) and *VR Lab* ($p < .001$), driven by a VISUALIZATION × ENVIRONMENT interaction in the *Heatmap* condition (higher workload in *MR Lab* vs. *VR Forest*, $p < .001$, and *VR Lab*, $p = .013$). Frustration was higher in *MR Lab* than in *VR Forest* ($p = .003$), see Appendix B.1.

3.1.4 *User Engagement.*

UES-SF scores were normally distributed ($p > .211$). An RM ANOVA revealed a significant main effect of ENVIRONMENT ($F(1.45, 33.45) = 22.02$, $p < .001$, $\eta_p^2 = .489$) with large effect size. No significant main effect of VISUALIZATION ($p = .142$, $\eta_p^2 = .075$, medium) or interaction ($p = .750$, $\eta_p^2 = .079$, medium) was observed, see Figure 3. Bonferroni-corrected post-hoc tests indicated higher engagement in *VR Forest* compared to *MR Lab* ($p < .001$) and *VR Lab* ($p < .001$), and a difference between *MR Lab* and *VR Lab* ($p = .002$). Subscale analyses showed higher engagement in *VR Forest* than in *MR Lab* and *VR Lab* across all subscales (all $p < .001$), see Appendix B.2 (Figure 6 and Table 1).

3.1.5 *Post-Study Feedback.*

Debriefing indicated *VR Forest* as the preferred environment ($N = 19$) and *MR Lab* as the least preferred ($N = 12$). *Histogram* was rated the most liked visualization ($N = 9$). Most disliked were *Center of Pressure* ($N = 11$) and *None* ($N = 10$). Participants generally agreed that VR/MR increased engagement (M = 3.92, SD = 1.39).

3.2 Qualitative: Semi-Structured Interview

Inductive thematic analysis revealed three themes: **Environmental Immersion & Gait Naturalness** Naturalness and realism were highlighted as key factors. *VR Forest* was "relaxing" (P14, P18), "real and beautiful" (P21), and "natural/less mentally pressuring" (P7), though some found it "boring" (P20). *VR Lab* was "safe and focused" (P1) but also "fake" (P14) or "monotonous" (P19). *MR Lab* felt "more real and comfortable" (P23, P22), but passthrough visuals were "pixelated" (P15) and "disorienting" (P1), causing participants to "walk very closely" (P17). **Feedback Clarity & Interpretability** *Heatmap* was consistently positive: "most information in least space" (P19) and "clear representation of data" (P11). *Histogram* was "clear to anyone" (P2), "attractive" (P6), "values are more predictable" (P9), but could distract attention: "trying to be careful" (P17) and occupy more space (P20). *CoP* was mostly confusing: "not understandable" (P12), "distracting" (P7), and "can't do my task properly" (P23). *None* allowed "walk freely" (P17), but lacked information. Pressure feedback was less effective in *VR Forest*, described as "annoying" (P15) and "distracting from natural walking" (P6), while in *VR Lab*, *Heatmap* "helped me understand pressure" (P5) and was "easy to concentrate" (P4). **User Comfort & Cognitive Load** Participants reported mixed emotional and physical experiences. *VR* walking was sometimes "more mentally and physically demanding" (P12). Physical discomfort arose from the orthosis "uncomfortable" (P7) and the HMD "too heavy" or caused "headache" (P7, P8). Participants suggested more engaging sceneries (P3).

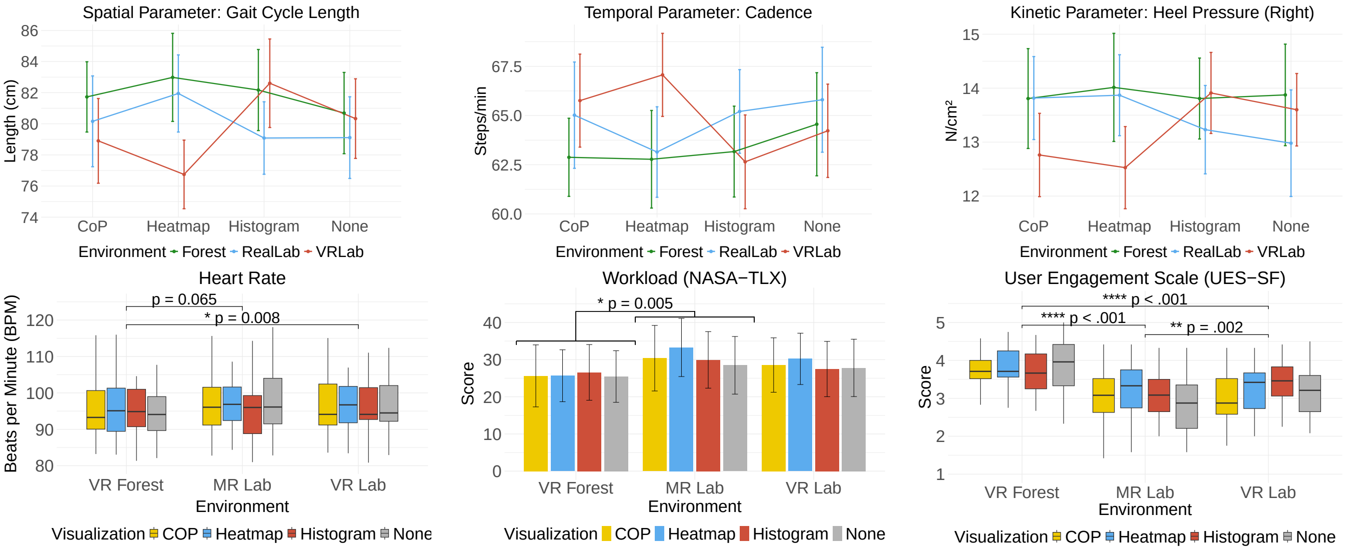

Figure 3: Top row (left to right): interaction plots for spatial (gait cycle length), temporal (cadence), and kinetic (heel pressure) gait parameters; bottom row (left to right): bar charts for heart rate, perceived workload (NASA-TLX), and engagement (UES).

4 Discussion

We conducted a study with 24 participants to examine how visual foot pressure feedback and environmental context affect objective and subjective measures in VR/MR treadmill walking. Results showed both factors influenced these outcomes. The *CoP* visualization had little effect, similar to baseline, as participants struggled to interpret it, suggesting task-dependency and not evident at fixed treadmill speeds. The strongest contrast emerged between *Histogram* and *Heatmap*, reflecting distinct pressure regulation strategies. The *Heatmap* promoted more focused, controlled gait, particularly in the *VR Lab*. Environmental context modulated these effects: the *VR Forest* supported larger steps, lower cadence, reduced heart rate, lower workload, and higher engagement, reflecting relaxation and enjoyment, whereas the *VR Lab* enhanced attention and deliberate gait control with the *Heatmap*. In contrast, the *MR Lab* offered limited benefit, as video passthrough reduced visual fidelity, lowering perceived performance and engagement, consistent with related work [16, 25]. These findings highlight a trade-off: naturalistic environments promote relaxed, comfortable walking, while controlled virtual labs support attentional focus and performance. Moreover, the environment can modulate the perception of visual cues, suggesting an interaction between context and feedback in shaping gait and user experience.

Implications and Design Recommendations: *(1) Support natural gait through naturalistic environments:* Use naturalistic environments to foster perception of relaxed walking and reduced workload, especially when orthoses alter gait or trust is developing; avoid visual feedback to preserve intuitive movement. *(2) Enable controlled gait through targeted feedback in stationary VR settings:* Stationary VR lab settings with heatmap feedback allow precise pressure regulation and step timing, making them suitable for corrective gait training with orthotic footwear. *(3) Adapt and align visual feedback to the training context:* Apply visual pressure feedback selectively; minimize during relaxation or orthosis familiarization to reduce workload, and use simple, interpretable feedback (e.g., histogram with orthosis rotation) to support understanding. *(4) Consider device dependency in MR gait training:* Ensure sufficient visual fidelity, as passthrough may limit performance; optical see-through displays may enhance precise foot–surface perception.

Limitations and Future Work: The study was restricted to healthy participants, limiting generalizability, and a fixed treadmill speed constrained natural gait adaptations. Furthermore, the MR setup with the Meta Quest 3 may have introduced confounding factors such as altered visual flow or passthrough fidelity, potentially influencing gait adaptation. Hardware limitations include the prototype insole being restricted to the right foot, and the system's end-to-end latency was not analyzed. Future work should evaluate and minimize such delays to ensure reliable real-time biofeedback. Follow-up studies should include patient populations, different footwear, and extended tasks.

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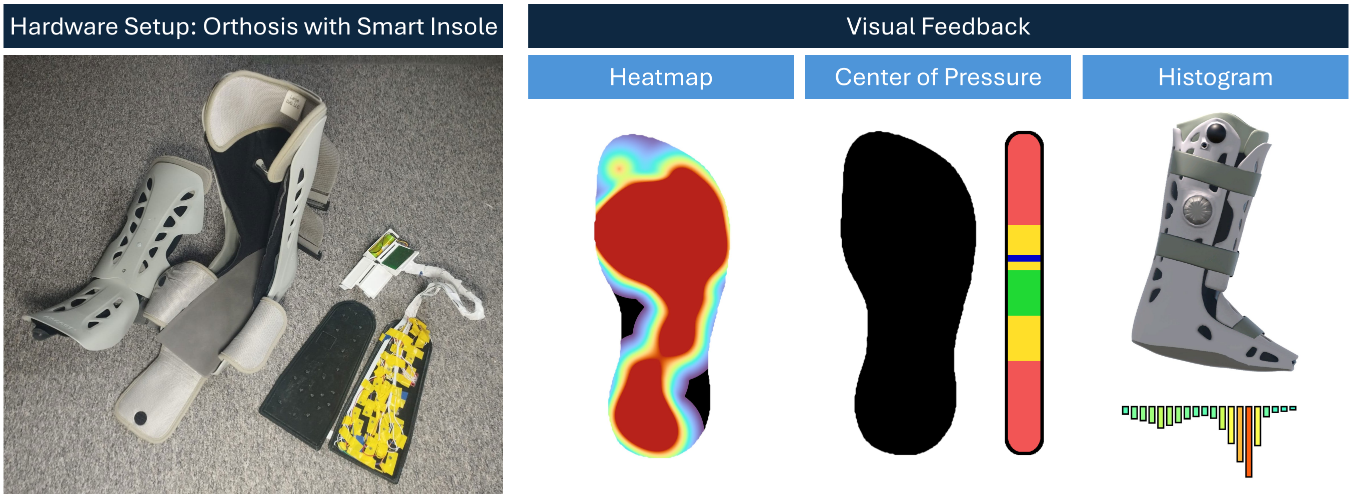
A Apparatus and Stimuli



(a) Controlled ankle motion boot with prototyped smart insole, force-sensing resistors, custom PCB with ESP32, and battery.

(b) Visual feedback stimuli including heatmap, center of pressure, and histogram.

Figure 4: (a) Hardware setup of the orthosis with the prototyped smart insole. (b) Implemented visualizations.

B Quantitative Results

B.1 Workload: NASA-RTLX Subscales

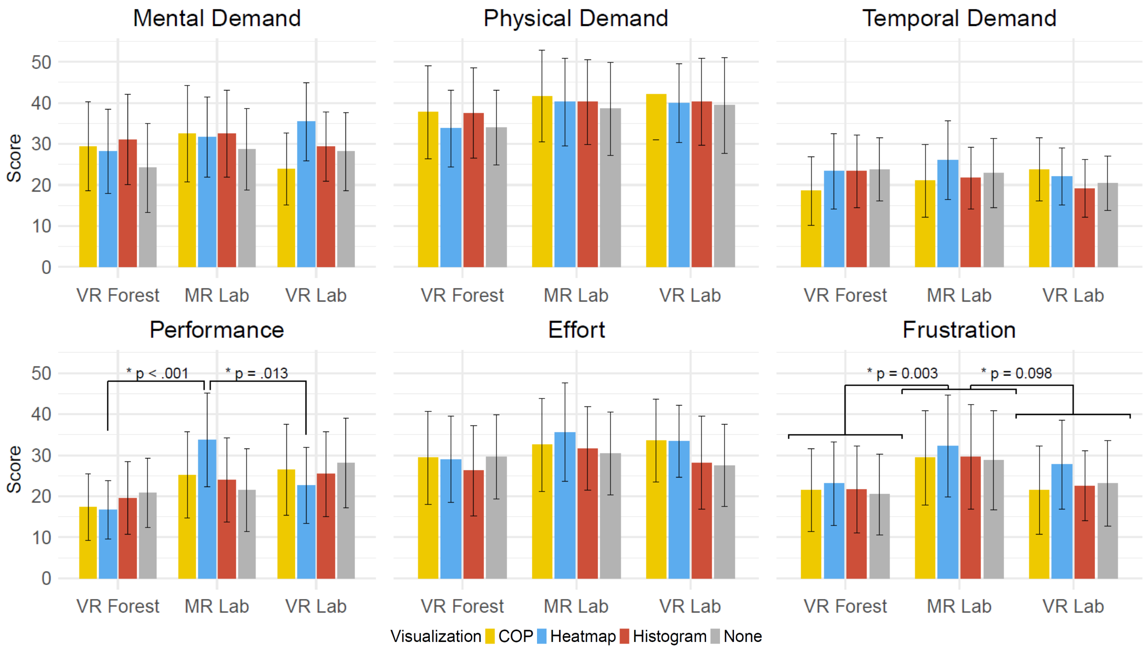


Figure 5: Bar charts of the six workload subscales, arranged in two rows: mental, physical, and temporal demand in the upper row, and performance, effort, and frustration in the lower row. Asterisks indicate statistically significant differences.

B.2 User Engagement: UES-SF Subscales

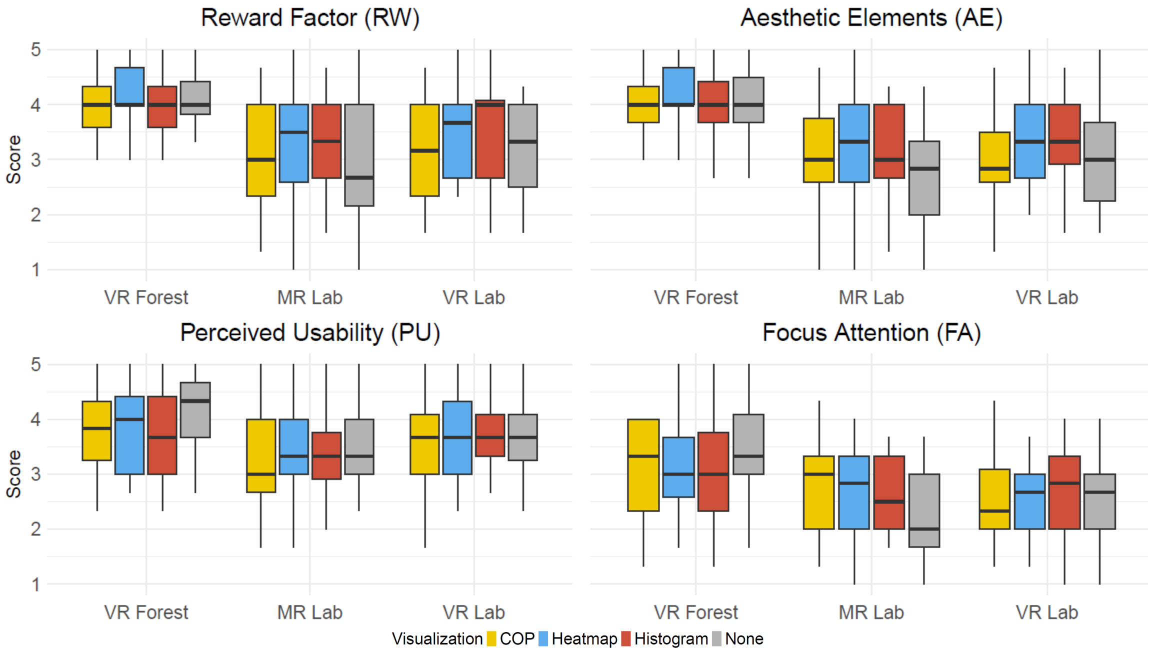


Figure 6: Boxplots of the four user engagement subscales, with reward factor and aesthetic elements in the upper row, and perceived usability and focused attention in the lower row. No statistical significance markers are included.

Table 1: ANOVA and post-hoc results for UES subscales (Bonferroni-adjusted).

Parameter	**Effect**	F	p	η_p^2	**Condition**	**Comparison**	p**-adj**	**Sig.**
Focus Attention	Env	10.02	< .001	.303	–	–	–	–
	Vis×Env	2.89	.024	.112	Heatmap	VR Forest > MR Lab	.029	*
					Heatmap	VR Forest > VR Lab	.024	*
					Histogram	VR Forest > MR Lab	.037	*
					CoP	VR Forest > VR Lab	.012	*
					None	VR Forest > MR Lab	< .001	***
					None	VR Forest > VR Lab	< .001	***
Perceived Usability	Env	9.57	< .001	.294	–	VR Forest > MR Lab	< .001	***
					–	VR Forest > VR Lab	.034	*
					–	MR Lab < VR Lab	.001	**
Aesthetic Elements	Vis	3.48	.020	.132	–	–	–	–
	Env	22.96	< .001	.500	–	VR Forest > MR Lab	< .001	***
					–	VR Forest > VR Lab	< .001	***
					–	MR Lab < VR Lab	.012	*
Reward Factor	Vis	4.15	.020	.153	–	–	–	–
	Env	18.57	< .001	.447	–	VR Forest > MR Lab	< .001	***
					–	VR Forest > VR Lab	< .001	***