Influence of Virtual Footwear on Gait Behavior, Embodiment, and Workload While Walking on a Treadmill in Virtual Reality

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Abstract

Virtual reality (VR) alters perception and motor behavior through avatar embodiment, where spatial judgments align with the body and gait is influenced by the Proteus effect and bodily affordances. While specific footwear, such as an orthopedic boot, affects gait in the real world (RW), direct comparisons with their VR representations remain underexplored. Therefore, we conducted a within-subject study with 18 participants, testing three footwear types (*shoes*, *socks*, and an *orthosis*) that were presented physically in RW or virtually in VR during treadmill walking. We measured gait parameters, embodiment, and workload. Results showed that the orthosis in RW influenced gait and perceived workload, whereas the orthosis in VR affected foot rotation angles and perceived control/agency without increasing workload. Qualitative feedback indicated that some participants experienced altered walking when using different footwear in VR. Our study highlights the impact of mismatches between physical footwear and their virtual representations, offering insights for VR-based gait training applications.

CCS Concepts

• **Human-centered computing → Virtual reality**.

Keywords

Foot Augmentation, Footwear, Virtual Reality, Visualizations, Gait

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1 Introduction and Background

Footwear affects gait through mechanical constraints and perceptual influences. In the RW, information about footwear properties is conveyed through somatosensory feedback, whereas in VR, foot-size perception can affect gait judgment and control [2]. Research shows that avatar fitness and embodiment acceptance can modulate physical exertion via the Proteus effect [3]. Moreover, virtual high-heels alter stride length, joint kinematics, and comfort, reflecting bodily affordances from visual constraints [4]. However, the interaction between RW and VR footwear is underexplored, although the effects of VR gait training may be driven by physical properties, visual representations, or both. To address this gap, we conducted a VR treadmill study where participants experienced *Shoes*, *Socks*, or an *Orthosis* either physically (RW) or visually (VR). We assessed gait parameters, embodiment, and workload to test how physical and virtual footwear influence motor and perceptual outcomes.

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2 Method

We conducted an experimental within-subject study to examine the effects of real and virtual footwear on gait, workload, and avatar embodiment. Independent variables were VR-Footwear and RW-Footwear, each with three levels: *Shoes*, *Socks*, and *Orthosis*. A balanced Latin square design was used for randomization and to avoid sequencing effects. Gait data was recorded using an instrumented treadmill, embodiment with Virtual Embodiment Questionnaire (VEQ) [5], and workload using NASA Task Load Index (TLX) [1].

Stimuli. The virtual avatar was based on the *Passive Marker Man* from Mixamo. The virtual environment was a replica of the laboratory and treadmill, created in Blender (v4.3). Footwear models (*Shoes*, *Socks*, and *Orthosis*) were also created in Blender. Figure 1 shows the first-person Unity visualizations of the created stimuli.

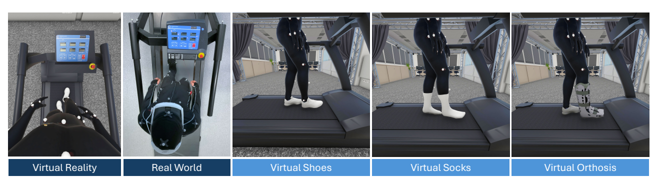

Figure 1: Conditions in RW and VR (Unity screenshots).

Apparatus. An OptiTrack motion capture system (ten PrimeX 13W cameras) with Motive software (v3.0.3, Baseline template) was used to create the avatar. Gait parameters were recorded with an instrumented treadmill (RehaWalk® FDM-THPL-S-2i, Zebris Medical GmbH) using Zebris FDM software (v2.0.4) at a sampling rate of 100 Hz. The VR environment was developed in Unity (v6000.0.46f1) and displayed via a Meta Quest 3 HMD. The application ran on a Windows 10 Pro PC (Ryzen 9 5900X, RTX 3070, 32 GB RAM).

Procedure and Task. In line with ethics and privacy regulations, participants gave informed consent and completed a demographic questionnaire. After a brief procedure explanation, they were fitted with an OptiTrack suit and footwear (orthosis on the right foot).

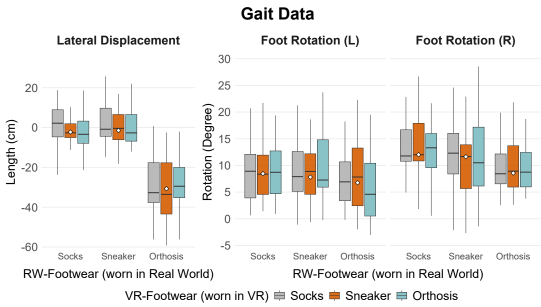

Figure 2: Gait Data (Zebris Treadmill)

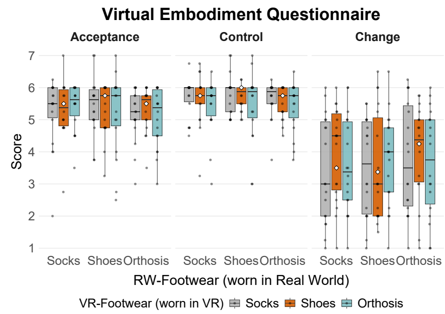

Figure 3: Embodiment (VEQ)

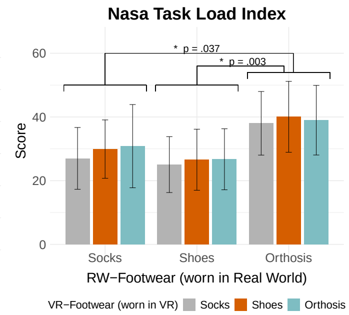

Figure 4: Workload (NASA-TLX)

Before each condition, they adopted a T-pose to calibrate the avatar. Participants were instructed to walk naturally on the treadmill at 2 km/h without holding the handles while viewing their footwear. Five 10-second gait trials were recorded per condition, followed by the NASA-TLX and VEQ. A survey concluded the session.

Participants. In total, 18 participants (16m, 2f; age = 20–31 years, M = 27.44, SD = 2.68) with backgrounds in engineering took part. Six participants wore glasses, and 15 reported prior VR experience. Familiarity with VR averaged 3.17 (SD = 1.29) on a 5-point scale. Shoe sizes ranged from EU 36–46 (M = 41.89, SD = 2.46).

3 Results

Quantitative Objective: Gait Data (Zebris Treadmill). A repeated-measures (RM) ANOVA with Greenhouse–Geisser correction revealed a significant main effect of RW-Footwear on temporal, spatial, and force-related gait measures ($p < .001$), with large effects between *Orthosis* and other conditions (see Fig. 2). A significant main effect of VR-Footwear was identified for right foot rotation, $F(2, 34) = 5.059$, $p < .012$, $\eta_p^2 = .229$ (between *Orthosis* × *Socks*: $p = .011$), and lateral displacement, $F(2, 34) = 5.419$, $p < .001$, $\eta_p^2 = .242$ (between *Sneakers* × *Socks*: $p = .016$). An interaction effect was found between VR × RW footwear for left foot rotation, $F(4, 68) = 4.079$, $p = .009$, $\eta_p^2 = .229$ (large effect size). Post-hoc analysis revealed that the RW-Footwear only affected left foot rotation when the VR-Footwear was an *Orthosis* (*Orthosis* × *Shoes*: $p < .001$; *Orthosis* × *Socks*: $p < .001$).

Quantitative Subjective: Embodiment (VEQ). An ART-ANOVA revealed a significant main effect of VR-Footwear on control/agency, $F(2, 136) = 3.289$, $p = .004$, $\eta_p^2 = .399$. However, no significant main or interaction effects were found for acceptance/body ownership or change. Several sub-items showed trends: for VR-Footwear *myBodyChange* ($p = .04$) and *causeMovements* ($p = .049$); for RW-Footwear *echoLargeThin* ($p = .02$), *myBody* ($p = .001$), *myBodyParts* ($p < .001$), and *causeMovements* ($p = .009$). After Holm-adjusted pairwise comparisons, only VR-Footwear (*Orthosis* × *Socks*) remained significant for *causeMovements* ($p = .049$) and *syncMovements* ($p = .024$). The results are presented in Fig. 3.

Quantitative Subjective: Workload (NASA-TLX). An RM ANOVA revealed a significant main effect for RW-Footwear, $F(2, 34) = 16.611$, $p < .001$, $\eta_p^2 = .494$, but no effect for VR-Footwear or interaction (see Fig. 4). Holm-corrected paired t-tests showed significant differences between *Orthosis* × *Shoes* ($p = .003$) and between *Orthosis* × *Socks* ($p = .037$), but not between *Shoes* × *Socks* ($p = .416$). The following subitems were significant: mental demand (*Orthosis* × *Shoes*: $p = .004$), physical demand (*Orthosis* × *Shoes*: $p < .001$; *Orthosis* × *Socks*: $p < .001$), effort (*Orthosis* × *Shoes*: $p < .001$; *Orthosis* × *Socks*: $p = .002$; *Shoes* × *Socks*: $p = .029$), and frustration (*Orthosis* × *Shoes*: $p < .001$; *Orthosis* × *Socks*: $p < .018$). Results of the overall workload are plotted in Fig. 4.

Qualitative Results. A post-experiment survey revealed three themes regarding the influence of VR-Footwear on gait: perceived influence, no influence, and uncertainty. Seven participants adapted their gait based on visual input, such as P14: "wearing the real orthosis but virtual was a shoe, it gave an illusion to walk better," or P18: "I changed my gait to accommodate ... what I saw." In contrast, six reported no effect, citing "no perceived difference" (P9). Five were unsure, as P4 stated: "I always notice my physical body."

4 Conclusion

Our results show that wearing the orthosis in RW significantly affected gait and increased cognitive workload, while virtual footwear influenced lateral displacement and foot rotation. An interaction effect indicates that differences in RW conditions emerged only when the virtual footwear was an orthosis. Qualitative feedback suggested that visual cues can shape motor behavior. These findings provide a basis for exploring how avatar footwear representations affect perception, embodiment, and gait characteristics. The study was limited by a small, gender-imbalanced sample. Future work should use larger samples and refine footwear visualization.

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