Foot Placement Feedback in Physical Training: Effects of Spatial User Interfaces on Performance and Workload in Virtual Reality

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Abstract

Agility ladder training is commonly used in fitness and therapy to improve coordination in lower-limb exercises by training precise foot placement. Previous research adapted this training approach to immersive environments and emphasized both the potential and the need for enhanced visual feedback in virtual reality (VR) to improve training outcomes. However, effective visual guidance for such tasks in VR remains underexplored, as it is unclear how spatial user interfaces (UIs) should be designed to support accurate foot placement. To address this gap, we conducted a within-subject study with 40 participants, investigating the effects of two visualization techniques: a *Foot-Aligned UI* (exocentric, attached to the feet) and a *Head-Aligned UI* (egocentric, floating in view); combined with color-coded performance feedback. Foot positioning accuracy, rotational control, success rate, and perceived workload were measured during VR-based agility ladder tasks. Results show that the *Foot-Aligned UI* significantly improved foot placement success rates without increasing cognitive load, compared to the *Head-Aligned UI* and *No UI* conditions, which was supported by qualitative feedback. In contrast, color-coded step feedback was perceived as helpful but showed no measurable performance benefit. Based on these findings, we derive design recommendations for spatial UIs to support lower-limb motor training in VR.

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CCS Concepts

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

Keywords

Virtual Reality, Foot Augmentation, Visual Feedback, Spatial User Interface, Agility Ladder Training

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1 Introduction

Precise foot placement plays a crucial role in many lower-limb motor tasks, including balance training, gait rehabilitation, and agility exercises [6]. In these contexts, accurate movement execution is not only essential for performance improvement but also for injury prevention and recovery. With the growing use of virtual environments in sports, exercise, and cognitive motor training [14, 40], VR-based training systems are gaining relevance for their ability to offer controlled, engaging, and repeatable training scenarios. For example, agility ladder training is a well-established method in which users perform predefined step sequences within a spatial grid, targeting coordination and foot placement accuracy [33]. This training method is used in physical therapy [8] and has been successfully implemented in immersive environments, demonstrating its suitability for VR-based motor training [24]. However, while VR offers promising opportunities to simulate and adapt such tasks, the lack of appropriate lower-limb visual guidance can limit its effectiveness [34]. Most existing VR applications focus on upper-limb interactions [13, 22, 28], whereas intuitive foot-based interaction has been less frequently explored. This is particularly a limiting factor in dynamic motor tasks, where visual attention is split between locomotion, coordination, and environmental awareness.

In general, foot augmentation in VR remains challenging due to reduced spatial awareness when looking downward and the cognitive effort required to manage visual attention during lower-limb tasks [26]. Therefore, the use of visual feedback such as directional cues, virtual indicators, or color-coded feedback can assist the user and enhance the spatial interaction [36]. Additionally, visual feedback is widely used in sports and rehabilitation as a form of biofeedback to correct motion and improve engagement [3, 11, 15]. For example, Ruddle and Lessels [38] demonstrated the benefits of using a walking interface for navigation in virtual environments. They emphasized that providing rotational, body-based information is highly beneficial for a range of spatial tasks, as it significantly improves the accuracy of angular adjustments. However, while visualization techniques are intended to assist users in guidance or precision tasks, their effectiveness strongly depends on how they are presented. For example, when visual cues are inappropriately placed or too abstract, they can increase cognitive load and distract, rather than support task execution. This highlights the importance of appropriate user interface (UI) design in lower-limb training applications.

To fully benefit from virtual training environments, effective visualization strategies must be implemented to ensure both accuracy and cognitive efficiency. Spatially anchored UIs, such as floating interfaces (e.g., Head-Up Displays (HUDs)), stationary in-situ elements, or body-attached augmentations, represent effective strategies for guiding physical movement. However, although HUDs have been widely studied for navigation and upper-limb interaction, their use for lower-limb tasks, such as agility training, remains underexplored. Moreover, it remains unclear how continuous, performance-related feedback can be effectively integrated to support lower-limb coordination in dynamic training scenarios.

To address this gap, we formulate two research questions (RQs):

- RQ1: How do Foot-Aligned UI (exocentric, fixed to the feet) and Head-Aligned UI (egocentric, floating in front of the user) spatial visualization techniques influence foot positioning accuracy, rotational control, success rate, and perceived workload during agility ladder exercises in VR?
- RQ2: To what extent does color-coded foot positioning feedback improve task performance and reduce perceived workload compared to the absence of such feedback?

In this paper, we present the results of an experimental user study in VR with 40 participants, investigating two visualization techniques for foot augmentation and examining the role of interactive, color-coded feedback on training performance.

Our main contributions are as follows: (1) empirical evidence demonstrating that exocentric (Foot-Aligned UI) visualization significantly improves training success rates compared to egocentric (Head-Aligned UI) or no interface (control condition), (2) insights into the effects of visualization type and color-coded feedback on spatial perception and cognitive demand, and (3) practical design recommendations for developing effective UIs tailored to lower-limb interaction in VR training contexts.

2 Related Work

This section reviews related work across three key areas: augmented agility ladder exercises (2.1), visual feedback in immersive training environments (2.2), and interface placement for visual feedback (2.3). We conclude with a summary of research gaps (2.4) and outline our contribution to the fields of VR training, spatial UI design, and the broader context of human-computer interaction (HCI).

2.1 Augmented Agility Ladder Exercises

Agility ladder training is widely used in fitness and therapy settings to improve coordination and physical function, particularly in older adults [8]. The method has also been investigated in dual-task scenarios that combine physical and cognitive training components [7].

In recent studies, this training approach has also been adapted to immersive environments. A study by Lei et al. [24] evaluated the validity of agility ladder training using a head-mounted display (HMD) and confirmed its applicability for physical exercises in VR. Building on this, Resch et al. [35] developed a VR training environment based on a floor grid and tested various visualization strategies. Their results showed that footstep visualizations achieved the highest success rates without increasing perceived workload. In a follow-up study, they compared agility training environments across three conditions: augmented reality (AR) floor projection in the real-world, AR passthrough, and VR [34]. While VR achieved comparable task performance to AR projection in the real environment, it was associated with increased mental demand when using a HMD. They recommended the integration of active performance feedback for foot placement accuracy and rotational control to extend the benefits of VR-based agility tasks. However, how such feedback should be displayed remains an open question.

To address this challenge, alternative feedback strategies should be considered that reduce the need to look downward, which often increases cognitive load and reduces spatial awareness. For example, a study by Kosmalla et al. [23] compared AR visualizations projected onto the wall versus the floor. Their results showed that wall-based projections led to higher agility performance, although participants preferred floor-based visualizations. This highlights the ongoing challenge of designing visual feedback that balances effectiveness with user preference. Therefore, it remains an open question how to display visual feedback in this training context.

2.2 Visual Feedback in Immersive Training Environments

Visual feedback plays a central role in virtual motor training environments, helping users interpret task performance, correct movement errors, and stay engaged. It can function as a reward mechanism [30] or provide real-time guidance by clarifying corrections or barriers [41]. A literature review by Diller et al. [10] classified visual feedback techniques in VR-based motor training according to their abstraction level, cue type, and use case. Common forms include positional and directional cues, textual overlays, or color-coded visuals, often applied across domains such as sports, rehabilitation, or motor learning. In particular, color-coded feedback has been identified as an intuitive and effective indicator of conveying performance quality (e.g., using red and green) [10]. Furthermore, visual cues have also been used to support joint-specific corrections, such as displaying limb angles to improve movement execution or to prepare users for subsequent steps [9].

In the context of lower-limb exercises, visual feedback has been used in treadmill-based gait training to improve step timing, coordination, and rotational control [4, 18]. For example, visual foot rotation feedback (via color-coded arrows) successfully reduced foot progression angle during walking tasks [18]. In another study, color-based biofeedback was employed to support children with cerebral palsy in developing regular stepping patterns [4]. Similarly, Amman-Reiffer et al. [1] demonstrated that foot visualization in VR increased foot placement accuracy and was favorably perceived by participants and recommended by therapists. While these examples highlight the effectiveness of immersive visual feedback, most approaches focus on generalized gait rather than task-based exercises.

2.3 Spatial Interface Placement

Previous research has investigated the effect of egocentric or exocentric views in virtual environments for several applications [21, 29]. Visual feedback in virtual environments is typically presented from a first-person, egocentric perspective. However, within this perspective, the spatial placement of feedback elements can vary. Depending on the task, it was shown that the spatial perspective of visual feedback influences perception, interaction, and cognitive load in various tasks [21, 29]. For example, Khadka and Banic [21] demonstrated that egocentric visualizations can improve task accuracy and reduce cognitive load in spatial memory tasks. Similarly, Mohler et al. [27] have shown that providing visual feedback can enhance egocentric interactions in virtual environments by improving distance estimation to targets on the ground plane. These findings suggest that spatial alignment between the user's body and the feedback location may influence task performance, which is particularly relevant for lower-limb tasks such as gait coordination.

Beyond perspective, the spatial placement of UI elements is essential in the design of interactive visual feedback systems. Previous work has compared different notification placement strategies in AR and VR, including 2D interfaces such as HUDs, floating elements, in-situ components, and body-based locations [16, 31, 39]. For example, displaying notifications on the wrist versus a floating HUD has been shown to affect user reaction times and task load [31]. Additionally, a study by Rzayev et al. [39] compared several UI placement strategies and recommended body-based or floating placements for general notifications, based on higher usability scores. However, these findings are task-dependent and were primarily evaluated for upper-limb interactions. The optimal placement of continuous, lower-limb performance-related feedback for physical training tasks remains largely unexplored.

2.4 Summary

Previous work has shown the promising use of virtual training concepts and visual feedback for guiding agility tasks. However, there is still a research gap regarding how to design visual feedback that improves training outcomes while reducing cognitive load. Several strategies have been proposed, such as floating interfaces or body-based visualizations, but these approaches have not yet been examined in the context of lower-limb training tasks. In particular, their influence on user performance and perceived workload remains unclear. To address this gap, we examine the use of body-attached and head-fixed visualizations for foot augmentation, in combination with color-coded performance feedback, during ladder exercises in VR. By evaluating these aspects, we aim to contribute to improved visual feedback techniques and provide design recommendations for future VR-based physical training applications.

3 Method

We investigated the effects of spatial visualization techniques for foot augmentation and color-coded feedback on foot positioning accuracy, rotational control, success rate, and perceived workload during physical tasks in VR. Our goal was to determine whether the type of visualization (foot-based vs. head-aligned interface) and the presence of foot positioning feedback influence foot placement performance and mental workload during agility ladder exercises. Therefore, we conducted an experimental user study based on a 2×3 within-subject design with two independent variables: VISUALIZATION and FIELD COLOR. VISUALIZATION comprised three levels: *Foot-Aligned UI* (exocentric, fixed to the feet), *Head-Aligned UI* (egocentric, floating in front of the user), and *No UI* (control condition). Both visualization frames of reference were selected because they offer distinct potential benefits: *Foot-Aligned UI* places feedback directly in line with foot movement, which supports focus and precise control, whereas *Head-Aligned UI* integrates feedback into the field of view, enabling participants to maintain situational awareness and potentially reduce workload. *No UI* was included as a baseline condition to assess task performance and workload without visual feedback, allowing the effects of the two visualization techniques to be contextualized relative to the absence of such feedback. FIELD COLOR had two levels: *Visible* (color-coded feedback) and *Invisible* (no feedback). A balanced Latin square was used to counterbalance the order of conditions and minimize sequence effects. We hypothesized that the VISUALIZATION technique would significantly affect foot placement performance. Specifically, we expected that the egocentric *Head-Aligned UI* would achieve comparable accuracy to the exocentric *Foot-Aligned UI*, without increasing cognitive load, relative to the *No UI* control condition. Furthermore, we hypothesized that the presence of *Visible* FIELD COLOR would improve foot placement accuracy without increasing cognitive load, compared to the absence of such feedback.

3.1 Stimuli

A virtual replica of the study laboratory was developed using the Unity game engine to ensure a high level of immersion and minimize external distractions, in line with related works [34, 35]. An agility ladder was visualized on the ground, covering a training area of 2×2 meters. The design of the grid and corresponding path visualizations followed the approach of Resch et al. [34]. The ladder consisted of 25 fields in a 5×5 grid, each measuring 40×40 cm.

The visualizations of the *Foot-Aligned UI* and *Head-Aligned UI* featured a curved, arc-shaped gauge surrounding each foot, similar to a semicircular dial. This dial served as a real-time visual indicator of foot rotation. Rotational accuracy was encoded using

Figure 1: Overview of the study design illustrating both independent variables and their corresponding levels: VISUALIZATION (*Foot-Aligned UI, Head-Aligned UI,* and *No UI*) and FIELD COLOR (*Visible* vs. *Invisible*). The upper row displays the three visualization conditions from the participants' view during the agility ladder task with invisible fields, and the lower row presents a third-person Unity view. A schematic sketch illustrates the differences between Foot-Aligned and Head-Aligned UIs.

a three-level color scheme: green (rotation $\leq \pm 2°$, optimal placement), yellow (moderate deviation, $\pm 2° < x \leq \pm 5°$), and red (high deviation, $x > \pm 5°$), as illustrated in Figure 1. These thresholds were adopted from prior work by Richard et al. [37], where they were successfully used for real-time feedback in gait precision tasks.

Each gauge featured a pointer that continuously displayed the current rotation angle of the foot. In the *Foot-Aligned UI* condition, the gauge was attached directly to the virtual representation of the user's feet and moved consistently with foot movements. In contrast, the *Head-Aligned UI* displayed both feet within a frontal interface that moved with the user's head orientation. Each foot was shown with a corresponding arc gauge and pointer, which updated in real time based on its rotational alignment. Both visualizations were implemented separately for the left and right foot and remained visible throughout the stepping tasks. We define the *Foot-Aligned UI* as an exocentric visualization, where feedback is attached directly to the foot. In contrast, the *Head-Aligned UI* represents an egocentric visualization, a floating interface within the user's field of view and moving with head orientation. The floating UI element was positioned at participants' eye height and at a fixed distance to ensure visibility without overlap or distraction. This placement also allowed participants to see the augmented foot rotation when looking straight ahead. The interface position was individually adjusted based on participants' body height to ensure it fit within their peripheral field of view without obstructing movement. For the *No UI* control condition, no additional visual feedback was provided beyond the displayed footprints within the agility ladder.

Participants were instructed to step as precisely as possible into the indicated fields, but without receiving real-time rotational feedback.

The FIELD COLOR was based on the visualization of footprints, dividing each field into two halves to enable separate foot placement. In the *Visible* condition, color-coded feedback was provided based on foot rotation accuracy, following the same threshold classification: green (correct), yellow (moderate deviation), and red (incorrect). When a foot was placed in the designated field area, the color indicating accuracy was displayed separately for the left and right foot. In the *Invisible* condition no color feedback was shown.

3.2 Apparatus

A motion capture (MoCap) system with ten cameras (type Prime^X 13W[1] from OptiTrack) was used to animate the VR avatar and precisely measure the foot placement of the participants. The cameras captured data at a frame rate of 240 Hz with a resolution of 1280 × 1024 pixels and were calibrated according to OptiTrack specifications, resulting in a mean wand error of 0.250 mm and mean ray error of 1.183 mm. Motive[2] software (version 3.1.4) was used for recording measurement data and skeleton generation based on the "Baseline" template, using 41 markers attached to the MoCap suit. A Meta Quest 3 HMD was used for the VR presentation, utilizing the Meta XR All-in-One SDK[3] (version 69.0.1) for development. To enhance wearing comfort and extend operating time, the HMD was equipped with an Elite Strap and battery pack. The virtual

[1]https://optitrack.com/cameras/primex-13w/
[2]https://optitrack.com/software/motive/
[3]https://assetstore.unity.com/packages/tools/integration/meta-xr-all-in-one-sdk-269657

avatar was based on the "Passive Marker Man" model from Mixamo[4] and animated using the real-time skeleton data provided by the OptiTrack system. The VR environment and visualizations were developed in Unity (version 2022.3.12f1), running on a Windows 10 Pro workstation (AMD Ryzen 9 5900X, 12-core, 3.70 GHz, RTX 3070, 32 GB RAM).

3.3 Procedure and Tasks

The study was conducted under controlled laboratory conditions. First, participants were informed about the study procedure and signed an informed consent form. Afterward, they were surveyed about their demographic data and prior experience with VR and agility ladder training. Next, participants were equipped with a MoCap suit (consisting of a jacket, pants, foot wraps, and a beanie) to which reflective markers were attached according to the predefined template. Participants then adopted a T-pose to calibrate the skeleton for motion tracking. After calibration, participants put on the HMD and were positioned on the starting field within the virtual ladder to align the camera perspective in Unity. The virtual avatar was scaled to each participant's height. Participants were instructed to step with both feet into each visible field to measure the initial contact. Once a field was entered, the next field was automatically displayed until the entire path was completed. Each path included eight visible fields, with an equal number of forward and lateral step directions. After completing a path, participants were guided back to the starting field using a ground floor visualization. Three different paths were performed per condition, resulting in a total of 24 entered fields. At the end of each condition, participants completed the NASA Task Load Index (TLX) questionnaire in VR to maintain immersion. This procedure was repeated for all subsequent experimental conditions. After completing all conditions, participants removed the HMD and completed a questionnaire with quantitative and qualitative items to reflect on their experience.

3.4 Measures and Data Analysis

The study included quantitative and qualitative data assessment. Quantitative results were analyzed using descriptive and inferential statistics with the rstatix package [19] in R. Qualitative feedback from open-ended responses was analyzed using thematic analysis.

3.4.1 Quantitative Objective: Rotation Angle, Foot Placement Accuracy, and Success Rate. Quantitative data were collected using the MoCap system at the moment of initial ground contact within the illuminated field. For each foot contact, heel and toe positions were recorded in both x and y directions (4 values per step). Each condition comprised three paths with 16 foot contacts each, resulting in 48 contacts and 192 data points per condition. The *rotation angle* was calculated separately for each foot upon placement, to determine inward (medial) or outward (lateral) rotation relative to the movement direction. Negative values indicated inward, positive values outward rotation. *Foot placement precision* was quantified by measuring the Euclidean distance from the center of each target footprint to the center point of the corresponding foot. Lower distances indicated higher placement precision. The *success rate* was defined based on the color-coded outcome of the foot placement in each subfield: placements resulting in a green field were assigned a score of 1.0 (100%), yellow fields a score of 0.5 (50%), and red fields a score of 0.0 (0%). The overall success rate for each condition was calculated as the mean of these values.

[4]https://www.mixamo.com/

3.4.2 Quantitative Subjective: Perceived Workload. To assess perceived workload of each condition, we used the raw NASA TLX [12]. Participants rated six subscales: mental, physical, and temporal demand, as well as performance, effort, and frustration. Ratings were analyzed using a two-way repeated measures (RM) ANOVA.

3.4.3 Quantitative Subjective: Experience Feedback (Post-Study Survey). After completing all conditions, participants filled out a questionnaire to provide both quantitative and qualitative feedback regarding their experience. Three quantitative subjective questions were rated on 5-point Likert scales [25] and analyzed descriptively. Participants evaluated their overall experience with the VR agility training (1 = very bad, 5 = very good), the perceived realism of the VR movement experience (1 = not realistic at all, 5 = very realistic), and their agreement with the statement: "The use of visual feedback was helpful in correcting my foot positioning" (1 = strongly disagree, 5 = strongly agree).

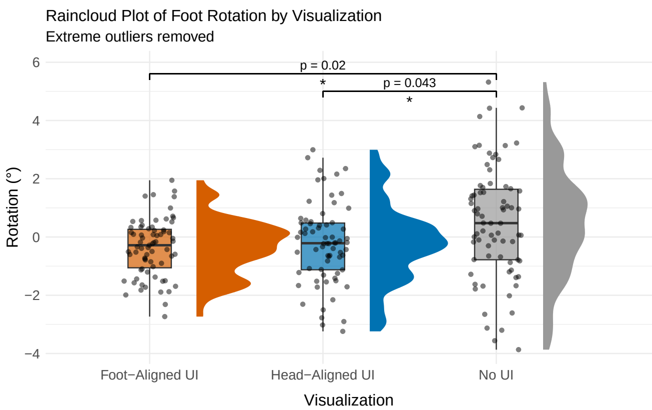
3.4.4 Qualitative Data: Open-Ended Responses (Post-Study Survey). Qualitative feedback was obtained through open-ended questions to gain deeper insight into the reasons for participants' preferred visualizations and their perceived usefulness in supporting accurate foot placement. An inductive thematic analysis [5] was performed to analyze the responses based on the predefined visualization categories. The anonymized data were transcribed, open-coded, and selectively coded by one researcher, and subsequently cross-checked by another researcher.

3.5 Participants

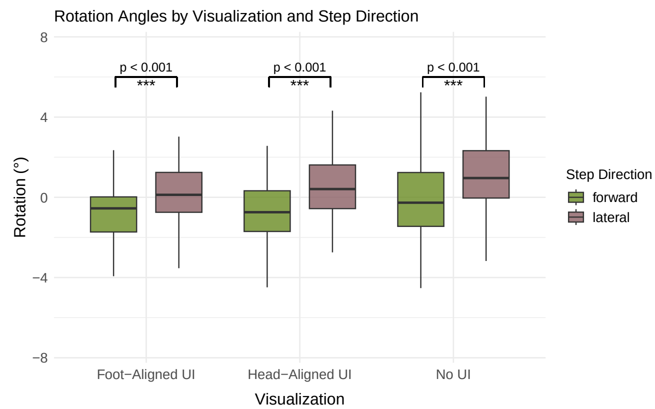
We recruited 40 participants (19 female, 21 male) through institutional mailing lists and personal contacts. Participants ranged in age from 19 to 32 years (M = 24.67, SD = 3.07) and represented ten nationalities with diverse backgrounds. In total, 22 participants reported prior experience with VR applications. Ten participants wore glasses, and four wore contact lenses during the study. Six participants reported prior experience with agility ladder training or similar coordination-based exercises. Participants rated their physical fitness on a scale from 1 (very low) to 5 (very high), with an average rating of 3.77 (SD = 0.92). Student participants received course credits for their participation. Participants were informed that they could discontinue or withdraw from the study at any time. All participants completed the study and were included in the final analysis. The study received ethical approval from the German Society for Nursing Science (No. 23-027) and was conducted according to privacy regulations and hygiene protocols for user studies as required by our institution.

4 Results

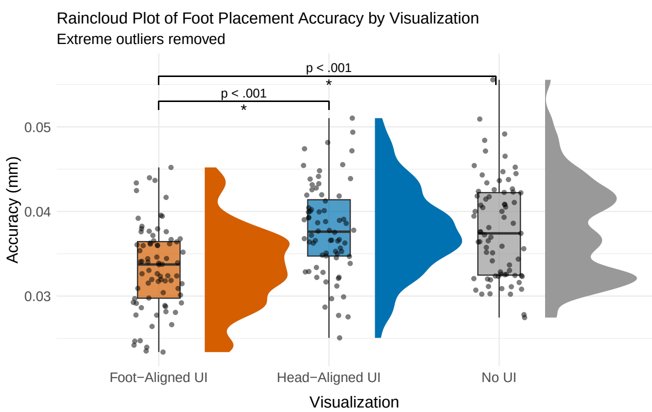
This section presents the quantitative results on foot rotation angles 4.1.1, foot placement accuracy 4.1.2, success rates 4.1.3, as well as subjective measures including perceived workload 4.1.4, ratings of experience from the post-study feedback 4.1.5, and qualitative insights from open-ended responses 4.2.



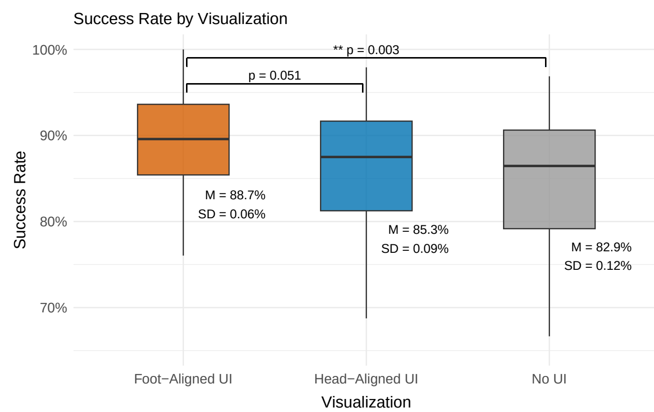
(a) **Raincloud plot of foot rotation angles by visualization type: half-violin plots, boxplots (25th–75th percentile), and jittered points; outliers (> 1.5 × IQR) removed.**



(b) **Boxplot of foot rotation angles by visualization type and step direction. Asterisks (*) indicate significant differences between step directions within each visualization.**



(c) **Raincloud plot of foot placement accuracy across Visualization levels. Lower values indicate greater precision.**



(d) **Boxplot showing success rates by visualization type. Asterisks indicate significant differences; mean and standard deviation are included.**

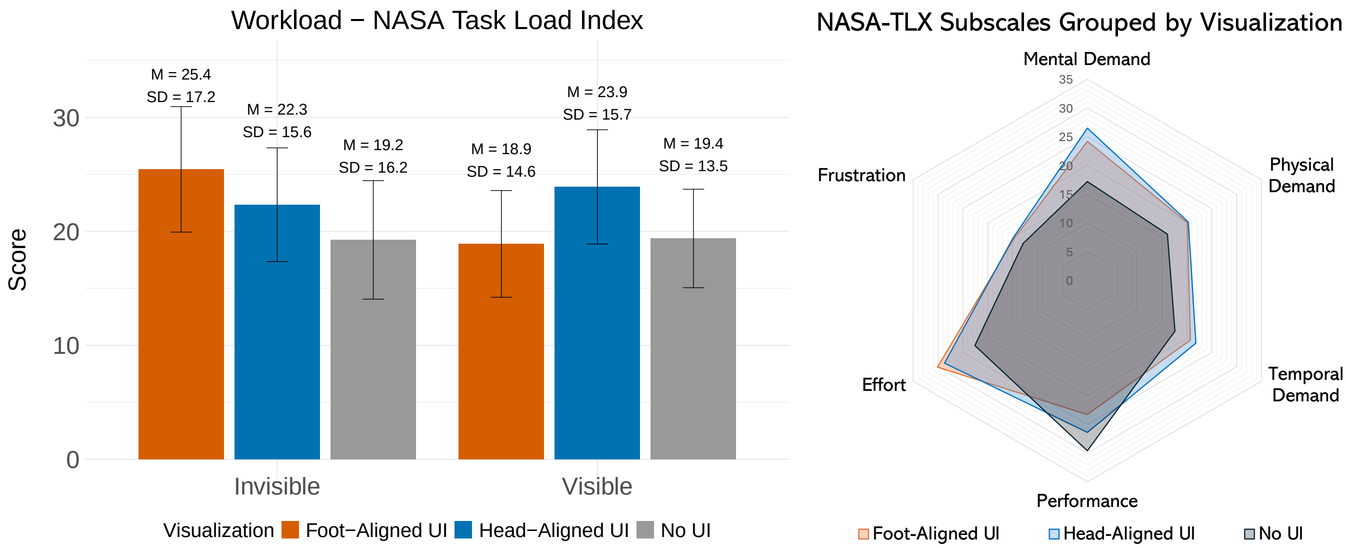
Figure 2: Overview of foot rotation and placement performance across visualization conditions: (a) Raincloud plot of foot rotation angles; (b) Boxplot by step direction; (c) Raincloud plot of placement accuracy; (d) Boxplot of success rates.

4.1 Quantitative Results

4.1.1 Objective: Foot Rotation Angle. To investigate the influence of both independent variables on foot rotation angles, a two-factor (3 × 2) RM ANOVA was conducted. The Shapiro-Wilk test showed no normal distribution for three conditions ($p \leq 0.038$). Therefore, a RM aligned rank transform (ART) ANOVA with Kenward-Roger corrected degrees of freedom was performed and revealed a statistically significant main effect of Visualization, $F(2, 185.25) = 13.676$, $p < 0.001$, $\eta_p^2 = 0.487$ (large effect size). In contrast, Field Color showed no significant main effect, $F(1, 185.24) = 0.43$, $p = 0.512$, $\eta_p^2 = 0.015$, and there was no significant interaction between Visualization × Field Color, $F(2, 185.11) = 0.54$, $p = 0.586$, $\eta_p^2 = 0.036$. Post-hoc pairwise Wilcoxon signed-rank tests with Holm-Bonferroni correction revealed significant differences between *Foot-Aligned UI* and *No UI* ($p = 0.020$), and between *Head-Aligned UI* and *No UI* ($p = 0.043$). However, no significant differences were found between *Foot-Aligned UI* and *Head-Aligned UI* ($p = 0.82$), nor between the *Visible* and *Invisible* foot placement feedback conditions ($p = 0.808$). These results indicate that both the *Foot-Aligned UI* and *Head-Aligned UI* conditions differed significantly from the *No UI* control condition in terms of foot rotation angles, indicating an influence of spatial visualization. However, the *Visible* foot placement feedback showed no significant effect.

The results for the Visualization conditions are presented in a raincloud plot (Figure 2a). The distributions for the *Foot-Aligned UI* and *Head-Aligned UI* conditions show a noticeable shift toward negative rotation angles, indicating a tendency for inward foot rotation. In contrast, the *No UI* condition peaks in the positive range, suggesting a higher prevalence of outward foot rotation.

Further analysis of foot rotation by step direction revealed a statistically significant difference between forward and lateral (left and right) steps ($p < .001$), as shown in Figure 2b. Forward steps resulted in more inward foot rotation, whereas lateral steps were associated with greater outward rotation.



(a) Bar chart showing overall perceived workload across the VISUALIZATION and FIELD COLOR conditions. Mean and standard deviation are indicated above each bar.

(b) Radar plot showing the distribution of NASA TLX subscale scores across the three VISUALIZATION conditions.

Figure 3: Subjective workload results based on the NASA TLX questionnaire. (a) Bar chart of overall workload for VISUALIZATION and FIELD COLOR; (b) Radar plot of six TLX subscales across the three VISUALIZATION conditions.

4.1.2 Objective: Foot Placement Accuracy. The Shapiro-Wilk test indicated that the foot placement accuracy data was not normally distributed in two conditions ($p \leq 0.004$). An ART RM ANOVA revealed a statistically significant main effect of VISUALIZATION on accuracy, $F(2, 185.53) = 24.403$, $p < 0.001$, $\eta_p^2 = 0.492$ (large effect size). However, FIELD COLOR did not yield a statistically significant effect, $F(1, 185.50) = 1.267$, $p = 0.262$, $\eta_p^2 = 0.025$ (small effect size), nor was a significant interaction effect found between VISUALIZATION × FIELD COLOR, $F(2, 185.25) = 0.192$, $p = 0.825$, $\eta_p^2 = 0.008$ (negligible effect size). Pairwise Wilcoxon signed-rank tests (Holm-Bonferroni adjusted) showed significant differences between *Foot-Aligned UI* and *Head-Aligned UI* ($p < .001$), as well as between *Foot-Aligned UI* and *No UI* ($p < .001$). However, no significant difference was found between *Head-Aligned UI* and *No UI* ($p = 0.62$), or between the *Visible* and *Invisible* field color conditions ($p = 0.37$).

These results indicate that the *Foot-Aligned UI* visualization led to the smallest deviations from the optimal placement and thus provided the highest accuracy. The findings are summarized in Figure 2c. No significant differences in placement accuracy were observed between forward and lateral steps.

4.1.3 Objective: Success Rate. A Shapiro-Wilk test revealed that the data were not normally distributed across all conditions ($p < .001$). A two-way ART RM ANOVA revealed a statistically significant main effect of VISUALIZATION on the success rate, $F(2, 185.49) = 11.286$, $p < 0.001$, $\eta_p^2 = 0.493$ (large effect size), however, no significant main effect was observed for FIELD COLOR, $F(1, 185.5) = 1.144$, $p = 0.705$, $\eta_p^2 = 0.006$ (negligible effect size). Furthermore, the interaction between VISUALIZATION × FIELD COLOR was not statistically significant, $F(2, 185.24) = 0.245$, $p = 0.782$, $\eta_p^2 = 0.021$ (small effect size). Pairwise Holm-Bonferroni adjusted Wilcoxon tests showed a statistically significant difference between *Foot-Aligned UI* and *No UI* ($p = 0.003$), indicating higher success rates in the *Foot-Aligned UI* condition. A comparison between *Foot-Aligned UI* and *Head-Aligned UI* showed a notable trend, but did not reach significance after correction ($p = 0.051$), while no significant difference was found between *Head-Aligned UI* and *No UI* ($p = 0.317$). The results are shown in Figure 2d.

4.1.4 Subjective: Workload. To investigate perceived workload across conditions, a two-factorial (3×2) RM ANOVA was conducted. However, Shapiro-Wilk tests indicated significant deviations from normality in all conditions ($p \leq 0.049$), except for the *Head-Aligned UI invisible* condition ($p = 0.063$). Therefore, an ART RM ANOVA with Kenward-Roger corrected degrees of freedom was performed.

Results indicated a significant main effect of VISUALIZATION, $F(2, 195) = 4.709$, $p = 0.010$, with a large effect size ($\eta_p^2 = 0.313$). The main effect of FIELD COLOR was not significant, $F(1, 195) = 1.736$, $p = 0.189$, with a small effect size ($\eta_p^2 = 0.078$). The interaction effect of VISUALIZATION × FIELD COLOR was also significant, $F(2, 195) = 4.775$, $p = 0.009$, showing a large effect size ($\eta_p^2 = 0.315$).

However, post-hoc pairwise comparisons using Wilcoxon signed-rank tests (Holm-Bonferroni adjusted) revealed no significant differences between individual conditions (all adjusted $p \geq 0.217$). An ART-ANOVA of the six subscales revealed several significant main and interaction effects (see Table 1). Pairwise comparisons using Wilcoxon tests revealed a significant difference for mental demand between *Head-Aligned UI* and *No UI* ($p = 0.043$). No other pairwise comparisons reached statistical significance. The main results are shown in Figure 3, including overall workload (Figure 3a) and the six subscales across visualization conditions (Figure 3b).

Table 1: ART-ANOVA results for TLX subscales

Scale	Effect	F	df	df_{res}	p	η_p^2
MD	Field Color	1.90	1	195	0.169	0.069
	Visualization	8.73	2	195	$<0.001^{***}$	0.403
	Field × Vis.	3.25	2	195	0.041^{*}	0.201
PD	Field Color	0.13	1	195	0.719	0.010
	Visualization	2.99	2	195	0.053	0.309
	Field × Vis.	3.61	2	195	0.029^{*}	0.352
TD	Field Color	0.19	1	195	0.659	0.018
	Visualization	2.44	2	195	0.090	0.310
	Field × Vis.	2.89	2	195	0.058	0.347
PE	Field Color	3.63	1	195	0.058	0.167
	Visualization	3.48	2	195	0.033^{*}	0.277
	Field × Vis.	3.79	2	195	0.024^{*}	0.294
EF	Field Color	0.17	1	195	0.681	0.009
	Visualization	5.01	2	195	0.008^{**}	0.358
	Field × Vis.	3.89	2	195	0.022^{*}	0.302
FR	Field Color	1.20	1	195	0.274	0.134
	Visualization	1.54	2	195	0.218	0.282
	Field × Vis.	1.77	2	195	0.173	0.311

Note: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$;
MD: Mental Demand, **PD**: Physical Demand, **TD**: Temporal Demand, **PE**: Performance, **EF**: Effort, **FR**: Frustration.

4.1.5 Subjective: Experience (Post-Study Feedback). Participants rated their overall experience with the VR agility ladder training on a 5-point Likert scale ranging from 1 (very poor) to 5 (very good), with a mean of 4.4 (SD = 0.63). Regarding the preferred Visualization, 29 participants rated the *Foot-Aligned UI* as the most helpful, followed by *No UI* (n = 6), and *Head-Aligned UI* (n = 5). The use of Field Color was considered helpful by 36 participants, while 4 perceived it as not helpful. The movement in the VR environment was perceived as realistic, as indicated by a mean rating of 4.13 (SD = 0.88) on a 5-point Likert scale (1 = not realistic at all, 5 = very realistic). Furthermore, 34 participants would recommend this type of training for agility exercises, while 6 would not. Additionally, 30 participants indicated that they would consider training regularly with a VR agility ladder in future, whereas 10 would not.

4.2 Qualitative Results

An inductive thematic analysis revealed four main themes: *Visual Realism and Spatial Interaction*, *Engagement in Virtual Training*, *Physical Discomfort*, and *Visual Feedback and Distraction.* These are described in the following subsections.

4.2.1 Visual Realism and Spatial Interaction. Participants described the VR environment as having a positive effect on training performance. It was frequently highlighted as "positive" (P1, P2, P11, P27, P30) and "helpful" (P8), for example, because "it was very interactive and interesting to see how precise my feet were or not" (ID3). One participant emphasized the clarity of the environment: "The environment was very clear to understand and easy to use" (P24), while another participant confirmed this impression, noting it was positive "because I knew the room" (P28). The realism of the exercise execution was also recognized: "I found the precision of my foot position very impressive" (P7). However, suggestions for enhancing realism were noted: "The feedback had a positive impact on performance, but I think the VR environment needs to be more realistic to have a further positive impact" (P24). In contrast, some participants experienced the environment as limiting because it was "unfamiliar" (P32). Others reported specific aspects that were unrealistic: "The fingers and wrist felt a bit unrealistic" (P29) and "the placement of the foot sometimes felt unrealistic" (P33). The lack of visual access to the real body influenced interaction: "I felt like I didn't have as precise control of where exactly I wanted to step" (P36) and "because I didn't see my actual feet, it's easier for me to coordinate if I could see them" (P3). One participant noted technical limitations, stating that "it was a bit delayed for me" (P6). Another participant suggested improving the interaction timing by recommending to "wait a bit longer before the next tile pops up to give the participant more time to evaluate their last step" (P36).

4.2.2 Engagement in Virtual Training. In general, virtual training was perceived positively, for example, "it really feels that you are doing some physical activity" (P25). One participant noted, "gamification of training did keep me engaged, which is good" (P29). Additionally, the system was considered promising for rehabilitation purposes, as one participant stated it "would be very helpful for physical therapy sessions" (P30). To further improve engagement in future virtual training scenarios, participants suggested adding dynamic elements such as a "parcours" (P16) or "a few obstacles so you don't get accustomed to it" (P21). Moreover, one participant proposed enhancing the immersive atmosphere by adding sound effects: "add some sports sounds so that people think that you are really competing or in a gym" (P25).

4.2.3 Physical Discomfort. Several participants expressed concerns regarding physical comfort, primarily related to the technical equipment. For example, it was noted that "the glasses are too heavy in the long term" (P22), and that "getting into the suit and having to wear the VR headset is kinda bothersome" (P36). Additionally, two participants reported short-term discomfort, mentioning "dizziness" (P13) and "slight eye pain" (P20).

4.2.4 Visual Feedback and Distraction. Visual feedback was generally perceived as beneficial. Participants stated that "it made the foot placement better" (P35), "made it easier to master the task" (P2), and "provided additional feedback that would not have been possible in the real world" (P37). One participant highlighted its usefulness: "because I received more information and wasn't focused on the environment. The focus was much more on my steps and my foot position" (P1). Furthermore, it was mentioned that "my foot position has improved" (P4), "because I paid more attention to the foot position" (P16, P17). Another noted that "the virtual environment and the foot-based UI, as well as the color fields very positive" (P2).

Participants also reported some limitations. For example, one participant mentioned that "the scales were too long" (P39), which could potentially lead to tripping, and suggested that "the scales should be designed (...) with smaller size" (P39). The *Head-Aligned UI* was perceived as distracting: "It annoyed me compared to the foot-based UI because I don't like having to multitask" (P37). In contrast, the *Foot-Aligned UI* was described as more intuitive: "With the foot-based UI, it was easier for me to focus on stepping into the next ladder square" (P37) and "the focus was on the feet" (P2). The *Visible* Field Color feedback was also highlighted positively. Participants mentioned that "the color helped to correct mistakes the next time" (P3) and that "I was able to adapt more quickly when I made mistakes" (P4). One participant noted that "the color feedback influenced (...) my movement" (P9), while another stated that it "helped improve the precision of subsequent steps" (P29). Furthermore, it was perceived as a form of motivation or a "reward system" (P10): "It didn't really help me improve (...) however, seeing it turn green was motivating" (P36) and "I was competing and trying to achieve more green colors" (P39). This visual cue led participants to "pay more attention as soon as it turned yellow" (P13) and to "adapt more quickly to errors" (P4).

5 Discussion

This study investigated two spatial visualization techniques for rotatory foot augmentation and performance feedback during agility ladder training in VR through an experimental user study with 40 participants. The quantitative results demonstrated that foot-augmented visualizations significantly improved rotational alignment and increased task success rates compared to conditions without UI-based guidance. Qualitative feedback complemented these findings by highlighting perceived benefits of visual augmentation, while also noting challenges related to interactive feedback and suggesting improvements. In the following, we discuss these results in relation to both research questions, outline design implications, and highlight limitations as well as directions for future research.

5.1 Influence of Visualization: Foot- vs. Head-Aligned UI (RQ1)

Regarding RQ1, which addressed how egocentric (*Head-Aligned UI*) and exocentric (*Foot-Aligned UI*) spatial visualization techniques influence foot placement accuracy and rotational control during physical training, our findings reveal clear differences between the interface types. Quantitative results show that both the *Foot-Aligned UI* and the *Head-Aligned UI* improved rotational control compared to the *No UI* control condition. These visualizations led to inward rotational adjustments and smaller angular deviations, suggesting that spatially aligned feedback effectively supports corrective foot movements. This aligns with qualitative statements emphasizing the added value of rotation feedback for step awareness. These findings are consistent with results from Richards et al. [37], who showed that real-time angular feedback in VR can reduce foot progression angles compared to unguided natural gait.

In contrast, only the *Foot-Aligned UI* led to significantly higher placement accuracy and success rates compared to the other conditions. Participants reported that this interface felt more intuitive and less demanding, as it was directly attached to the feet and aligned with their focus during stepping. While overall workload ratings showed no significant differences between conditions, mental demand was significantly higher in the *Head-Aligned UI* than in the *No UI* condition. Furthermore, several participants described the *Head-Aligned UI* as distracting, as it was difficult to focus due to the divided attention. This supports the interpretation that egocentric, floating visualizations may introduce unnecessary cognitive load in tasks that require precise spatial control of the lower limbs.

These findings partially contradict our hypothesis that both UIs would yield similar improvements without increasing cognitive demand. While both visualizations improved rotational control, only the *Foot-Aligned UI* achieved better placement performance outcomes and was perceived as less intrusive. Therefore, the use of exocentric lower limb augmentation is more effective for guiding foot movements in agility ladder training tasks. These results demonstrate both the potential and limitations of rotational foot augmentation. While foot-based visualizations can enhance task performance and enable real-time correction, their effectiveness depends on spatial alignment and cognitive load.

5.2 Impact of Color-Coded Foot Placement Feedback (RQ2)

Regarding RQ2, which examined the impact of color-coded foot positioning feedback on task performance and cognitive load, no significant effects were observed. Contrary to our hypothesis, the *Visible* Field Color condition had no significant effect on foot rotation, placement accuracy, success rates, or perceived workload. One possible explanation for the lack of measurable effects is that the color feedback was only displayed after each foot was placed, rather than being updated continuously during movement. This design decision intended to avoid overlapping with the real-time visualizations of the UI conditions, but may have limited the ability to guide adjustments during stepping. Although the quantitative results revealed no statistical differences, subjective feedback was predominantly positive, with 90% of participants rating the feedback as helpful. This aligns with the qualitative data, which indicated that the feedback helped participants focus more on their performance. Overall, the color feedback served primarily as a motivational cue, which many participants perceived positively. These findings are supported by related work showing that color-based feedback can influence emotional responses and cognitive focus [32]. These findings suggest that color-based performance feedback can function as a reward system that reinforces the gamified nature of the training. It may motivate participants to improve their performance while maintaining focus on the next step. However, to fully benefit from this feedback type, future implementations should address its limited influence on objective performance outcomes by enhancing its integration with task-relevant interactive cues.

5.3 Implications and Design Recommendations

We successfully developed an active real-time visual feedback system for foot rotation angles that improved both rotational control and placement precision, without increasing perceived cognitive load. However, our findings also suggest that poorly placed visual interfaces can result in performance outcomes comparable to having no feedback at all, which makes them ineffective for lower-limb guidance. Our results show that both *Foot-Aligned* and *Head-Aligned* visualizations supported rotational control to a similar extent. However, only the *Foot-Aligned UI* enabled precise foot placement within the target fields, whereas the *Head-Aligned UI* led to greater positional offsets, indicating reduced spatial accuracy despite comparable rotational guidance.

Based on these insights, we provide the following design recommendations for researchers and practitioners developing spatial feedback systems in lower-limb physical VR training:

(1) **Attach Rotational Feedback Directly to the Foot:** Based on our objective findings, we recommend embedding real-time rotation indicators in the foot representation rather than presenting them in a floating (egocentric) UI, to maintain spatial alignment and reduce interpretation effort. This principle can be extended beyond agility ladder tasks to applications such as gait training [17] and motor rehabilitation [42], where lower-limb guidance is essential.

(2) **Design for Accessibility and Perspective:** Participant feedback indicated that inappropriate UI element size and placement may cause tripping, while unsuitable viewing angles may result in distraction. Therefore, visual foot-aligned elements should be designed with appropriate size and color contrast, and adjusted according to the avatar's size and the participant's viewing angle.

(3) **Design for Task Specificity:** Participants preferred feedback placed directly at the foot, as it supported their focus on positioning, whereas unspecific or misplaced cues reduced effective lower-limb guidance. Therefore, spatial UIs should be aligned with the movement demands of the task and tailored to the targeted performance outcome. For example, a continuous semicircular dial can enhance rotatory foot placement and success rates in stepping tasks, whereas adaptations may be required for gait training scenarios focusing on symmetry or balance (e.g., arrows as discrete indicators for directional corrections).

(4) **Use Color-Coded Feedback for Motivation and Not Just Correction:** While quantitative results showed that color-coded cues (e.g., red/green indicators) did not directly improve performance metrics, participant feedback indicated that such feedback supported focus during repetitive step sequences and served as a reward system to help users stay focused and motivated. In line with prior research [2, 10, 36], which highlights the positive effects of visual color feedback in exercise and rehabilitation, we recommend integrating real-time color-coded cues to maintain attention and encourage corrective adaptation in lower-limb training tasks.

(5) **Incorporate Gamified Elements to Support Engagement:** Participants' feedback highlighted that gamified elements (e.g., obstacles) and immersive environmental factors (e.g., competitive or gym settings, auditory cues) could positively enhance engagement during training tasks, consistent with prior findings [20]. Depending on the application context (e.g., rehabilitation or sports training), such elements should be adapted beyond the neutral laboratory environment to create more realistic and motivating scenarios. We recommend combining environmental factors with color-coded feedback as part of gamification (e.g., a scoring system based on success rates) to serve as reward mechanisms, enhancing engagement, focus, and training motivation.

5.4 Limitations

While our study offers valuable insights into the effects of visual feedback on foot rotation and placement accuracy, several limitations should be acknowledged. The participant sample primarily consisted of young, healthy individuals with moderate fitness levels. As a result, the findings have limited generalizability to broader populations, such as older adults or individuals with motor impairments (e.g., stroke patients). Nevertheless, the tested visualizations may serve as promising visual guidance tools for such groups in future adaptations of the training context. The results and derived foot-based UI design recommendations are specific to the investigated tasks and training setting and may not directly apply to natural gait scenarios. Moreover, the study was conducted using a specific technical setup in a short-term experimental session. Potential long-term effects or progressive training adaptations over time were not examined and require further investigation.

5.5 Future Work

To address the current limitations, future work should explore several directions. Follow-up studies should include a more diverse participant sample (across age groups and physical abilities) to enhance the external validity and applicability of the findings. In addition, exploring long-term training effects and validating the system in rehabilitation contexts (e.g., physical therapy) could provide valuable insights for applications involving patients with gait impairments. Based on participants' feedback, the integration of additional gamified elements (such as obstacles) could help maintain motivation and contribute to continued engagement over time. The role of field color should also be examined further to explore ways of increasing its functional relevance and integration into real-time corrective feedback. Finally, to extend beyond agility ladder training, the proposed feedback system for rotatory foot placement should be evaluated in natural gait contexts, such as treadmill walking or indoor navigation tasks. This would help determine its effectiveness in broader applications, including rehabilitation, sports, and everyday mobility.

6 Conclusion

This study investigated the effects of egocentric (*Head-Aligned UI*) and exocentric (*Foot-Aligned UI*) spatial visualizations on foot placement accuracy, foot rotation, success rates, and perceived workload during virtual agility ladder exercises. The results showed that the *Foot-Aligned UI* significantly improved foot placement accuracy and led to the highest success rate (88.7%) compared to the *Head-Aligned UI* and *No UI*. These findings highlight the potential of exocentric, foot-based visualizations to facilitate accurate foot placement without adding cognitive load. This insight contributes to the future development of feedback systems designed to improve movement precision in virtual physical training applications. Based on our findings, we propose design recommendations for adapting rotational foot feedback to a broader range of walking-related activities, aiming to extend its applicability beyond agility training to general gait tasks and rehabilitation contexts.

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