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The Influence of Augmented and Virtual Reality Environments on Foot Positioning Success and Workload in Agility Ladder Exercises

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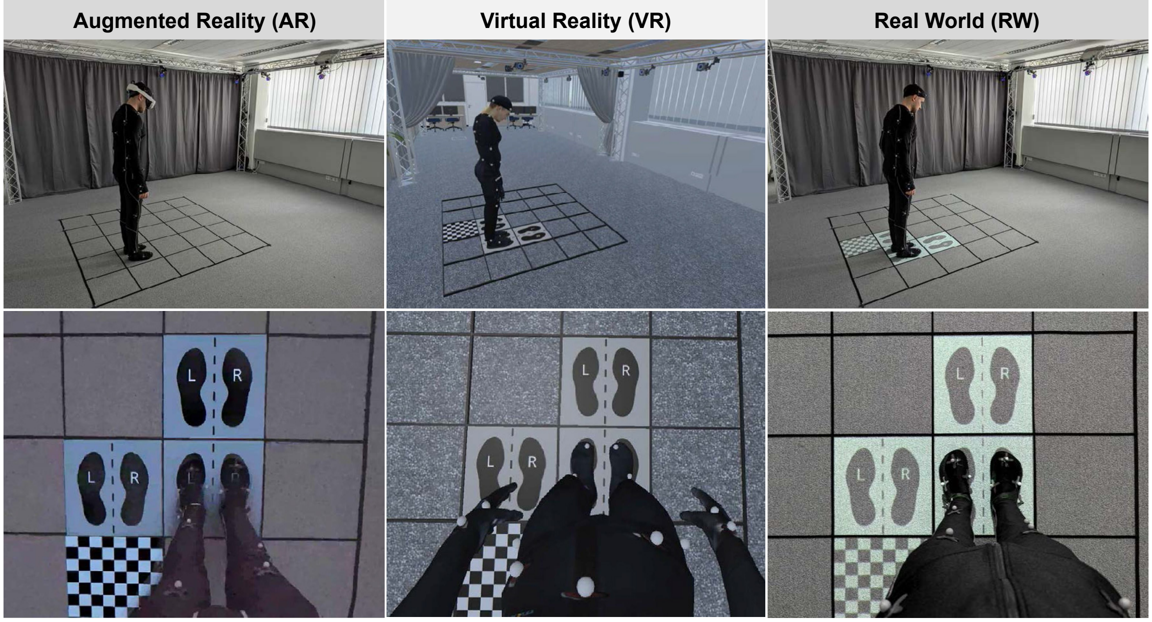
Augmented Reality (AR)

Virtual Reality (VR)

Real World (RW)

Figure 1: The six images display the three environments: *AR*, *VR*, and *RW* (from left to right). The top row shows the spatial perspective, while the bottom row presents the participants' view. In AR, participants see the *Footsteps* visualization via passthrough of the headset, in VR through a Unity scene, and in RW via a projector.

ABSTRACT

Agility ladder training is used by athletes and in rehabilitation to improve coordination and motor skills. Research highlights the potential of visual feedback in virtual reality (VR) to enhance agility ladder training compared to conventional real-world (RW) methods. Moreover, the integration of mixed reality technologies introduces new possibilities for rehabilitation through novel agility ladder concepts. However, the impact of augmented reality (AR) and VR on foot positioning success rates and foot rotation angles compared to RW environment remains underexplored. We conducted an experimental study with 24 participants to assess foot positioning success rates, rotation angles, and perceived workload in AR, RW, and VR environments, using two different visualizations: empty fields and footsteps. The results showed that AR led to significantly lower foot positioning success rates compared to both RW and VR, while VR resulted in greater inward foot rotation angles. Additionally, participants reported a significantly higher perceived workload in AR, which was consistent with qualitative feedback from post-study questionnaires. Our findings reveal the need for improved visual feedback in immersive training environments to enhance performance and reduce cognitive load. We also discuss the challenges of using AR passthrough technology for agility ladder training and provide recommendations for future rehabilitation applications.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented Reality, Virtual Reality; Human-centered computing—Visualization—Empirical studies in visualization.

1 INTRODUCTION

Agility Ladder training is a widely recognized method in both sports and rehabilitation, used to enhance coordination and motor skills in athletes or patients [20, 5, 11]. This type of physical training is based on a visual ladder placed on the ground, which serves as a guide for foot placement. The ladder consists of multiple squares arranged in either a linear or grid pattern [14]. Depending on the training goal, this approach allows for varying levels of difficulty

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through different step sequences and speed changes. Participants are instructed to step into the squares of the ladder in a predefined sequence. The purpose of this physical training is to enhance lower limb motor coordination and ensure accurate steps without errors, such as stepping outside the defined areas, to achieve a high success rate. In physical therapy, this training approach is applied to improve foot placement accuracy in patients with various foot conditions or after strokes [6]. For example, patients with abnormal gait patterns, such as inward or outward foot rotation, often show incorrect foot placement with increased or decreased rotation angles [21]. However, patients rely on the guidance of physical therapists to receive feedback on their gait and to improve their success rate in achieving correct foot positioning. Without professional guidance, patients may have difficulties performing the exercises correctly and therefore limited in their ability to train independently, particularly at home.

For this reason, current research focuses on patient-centered solutions that provide active training support in rehabilitation [13, 1]. One use case is the application of visual feedback in mixed reality (MR), including augmented reality (AR) and virtual reality (VR), which has shown promising results for training sessions [31, 16, 24]. Immersive environments, such as VR, create a fully virtual setting for participants, while AR overlays additional visual information onto the real environment to enhance interaction. The application of AR training promises greater value compared to traditional training methods, as it allows users to remain in the real world while benefiting from augmented visual guidance [15]. Furthermore, the development of interactive training approaches with additional visual feedback in VR can help to improve specific aspects of training performance, such as movement accuracy [9, 2, 3]. However, despite the growing development of novel training concepts, the impact of AR and VR technology on foot positioning success rates and foot rotation angles has not been validated in comparison to conventional real-world (RW) agility ladder training. It is important to validate AR, RW and VR environments to understand how the different technical capabilities of each medium affect the performance and cognitive load of participants during the training. This comparison will provide valuable insights into the strengths and limitations of each environment for future patient-centered rehabilitation programs. Therefore, the following research questions (RQ) arise:

RQ1: To what extent do immersive training environments and visualizations influence foot positioning success rates and foot rotation angles compared to conventional RW training?

RQ2: To what extent do immersive training environments and visualizations affect the perceived workload compared to conventional RW training?

Based on these insights, our objective is to develop a training environment that provides enhanced support for patients in the rehabilitation process. Therefore, we conducted a controlled laboratory study to investigate the effects of AR, RW, and VR environments, as well as two visualizations, on foot positioning success rate, rotation angles, and perceived workload in agility ladder training.

In this paper, we present the results of an experimental user study involving 24 participants, measuring objective success rates and rotation angles, subjective workload, and qualitative feedback gathered through post-study questionnaires. The results indicated that AR led to significantly lower foot positioning success rates compared to both VR and RW, while VR showed significantly greater foot rotation angles. In conclusion, immersive training environments should focus on enhanced visualizations to improve training performance and reduce cognitive load.

2 RELATED WORK

Our work builds on existing research in the field of visual feedback for foot positioning training, while also exploring technological comparisons between AR, RW, and VR environments. In our context, we define VR as a fully immersive environment, where users are entirely immersed in a virtual setting using an head-mounted display (HMD). AR is defined as utilizing video passthrough technology, where digital elements are overlaid onto the real world through an HMD. Lastly, the RW environment does not involve an HMD. To ensure comparability, visual feedback is provided through projection-based AR, with visual cues projected onto the ground via a projector. This section outlines current research on the development of training systems with visual feedback, AR-Based Visual Feedback, and VR-Based Visual Feedback. Finally, we summarize the previous work and highlight how our research aims to contribute to this field.

2.1 Development of Training Systems with Visual Feedback

Recent research highlights new developments in interactive training systems that could enhance the performance of ladder drills compared to conventional training methods [2, 9, 25, 4]. For example, Gil et al. [9] developed a multi-modal agility ladder equipped with ultrasonic sensor-based step detection and visual light-emitting diode (LED) feedback. The system measures step accuracy and step time, and is able to communicate with a mobile application via Bluetooth. Furthermore, Apostolidis et al. [2] presented a 'smart ladder for interactive fitness training,' designed as a cost-effective solution providing real-time performance feedback through visual LED displays and Internet of Things (IoT) sensors, accessible to athletes and coaches via a web application. The results of their study showed that the smart ladder led to high user satisfaction, significantly improved performance after seven weeks of training, and fewer mistakes after the first week. These studies illustrate new physical developments for ladder training, particularly in how sensor technologies are used to provide visual LED feedback. These outcomes demonstrate the effect of visual feedback on agility ladder training in the RW environment and highlight its future potential. However, further research is needed to validate and extend these developments for patient-centered rehabilitation.

2.2 AR-Based Visual Feedback

The application of AR for interactive training is often implemented using projection-based visualizations in real environments [28, 30, 29]. For example, Sekhavat and Namani [27] compared treadmill training with video projection-based AR to visual monitor-based feedback. The results showed significantly better performance with the projection-based AR system compared to the monitor-based platforms, which could also be beneficial for various rehabilitation use cases. In addition, Kosmalla et al. [17] investigated two projection methods (floor and wall projections of footsteps) for an augmented agility ladder in a RW environment. In a study with 12 participants, they evaluated perceived workload using the NASA Task Load Index (TLX) [10] questionnaire and agility using the Illinois Agility Test [8]. The results indicated that wall projections led to higher agility skill levels and were preferred by the participants. However, while projection-based AR has shown promising results in some studies, it has limitations in terms of immersion and portability compared to HMD-based AR systems. Projection systems often restrict the user's perspective, require specific setups, and limit mobility, making them less practical for home-based or mobile training applications. The use of an HMD with AR passthrough as a portable solution in flexible settings has not yet been tested in agility ladder training contexts. Therefore, further research is necessary to evaluate and compare the overall efficiency of both systems.

2.3 VR-Based Visual Feedback

VR has been successfully applied in several areas of rehabilitation, such as stroke recovery and balance training [26, 22, 18]. A systematic literature review by Howard [12] concluded that VR programs are more effective than traditional rehabilitation programs. It was emphasized that further research is needed to gain a deeper understanding of VR training programs and their impact on rehabilitation outcomes. Based on these advantages, a few studies have specifically explored the use of VR for agility ladder training [19, 23]. For example, Lei et al. [19] investigated the validity of using VR headsets for agility ladder training. The study found no significant deviation in movement consistency between real and virtual environments. This result suggests the potential of VR technology to improve agility training methods, especially with further advancements in these technologies. Additionally, Resch et al. [23] explored the effectiveness of four different visualizations for agility ladder training in VR. The results showed that visualizing footsteps improved foot positioning within the ladder without increasing the workload, while participants preferred empty fields for their simplicity. Nevertheless, further research is needed to assess how immersive environments can support active foot placement during ladder training. While current studies provide insights into foot positioning success, detailed information on foot rotation angles remains unvalidated, highlighting the need for more comprehensive assessments.

2.4 Summary

In summary, the use of additional visual feedback has shown promising results in improving the accuracy of foot positioning and overall training success. The application of projection-based AR in RW, as well as the integration of VR, offers several advantages over traditional or screen-based training methods. Previous research has highlighted the need for follow-up studies to investigate the long-term effects and implications of visualization in different environments. However, it remains unclear how the use of AR through an HMD influences both accuracy and overall training performance compared to RW and VR. By addressing our research questions, we aim to fill this gap and contribute to the development of new immersive training environments. Our research will contribute to a better understanding of the technical application of AR via an HMD, in comparison to VR and projection-based AR in RW. It will provide new insights into the influence of the environment on foot positioning accuracy and cognitive load in agility ladder training.

3 METHOD

We conducted an experimental user study to investigate the effect of agility ladder training in AR, RW, and VR environments on foot positioning success rate, rotation angles, and perceived workload. The study is based on a within-subject design with two independent variables: ENVIRONMENT and VISUALIZATION. The ENVIRONMENT variable comprised three levels: *AR*, *RW*, and *VR*. The VISUALIZATION variable included two levels: *Empty Fields* and *Footsteps*. To avoid sequencing effects, the order of conditions was randomized using a 6 × 6 balanced Latin Square design.

We hypothesized that using *Footsteps* visualizations would lead to more accurate foot positioning across all three environments without increasing the perceived workload. Additionally, we hypothesized that training in *AR* and *VR* environments would result in similar foot positioning accuracy, rotation angles, and perceived workload compared to training in *RW*.

3.1 Stimuli

The agility ladder consisted of 25 square fields with 40 centimeter sides, arranged in a 5 x 5 grid. This configuration was created to enable forward steps and multiple lateral steps side by side, which are essential movements in agility training. In the *RW* environment, the grid was created using Velcro strips attached to the floor, which served as the visual reference for the agility ladder. This setup was tracked by our motion capture (MoCap) system and replicated in the AR and VR environments to ensure consistency across all conditions. Visualizations of *Empty Fields* or *Footsteps* in the *RW* environment were projected onto the grid using a projector.

The *AR* environment was implemented using the passthrough mode of the Meta Quest 3 headset. To enhance realism, the *VR* environment was recreated as a 3D replica of the room, with a visualized grid on the floor (see Fig. 1). The 'Passive Marker Man' avatar from Mixamo [1] was used for the VR environment, animated using the skeleton from OptiTrack. The virtual avatar was scaled according to the participant's height. The visualizations of *Empty Fields* and *Footsteps* was utilized as recommended by Resch et al. [23].

A visible starting field was used to position the participant in the center of the first row of the grid. Three different paths were designed to allow each condition to be repeated three times with the same visualization within the same environment. Each path consisted of eight visible fields, which participants had to step on with both feet (see Fig. 2). Each path included four forward steps, two steps to the left, and two steps to the right, resulting in a total of 24 fields for each condition. The paths were presented in a randomized order with either *Empty Fields* or *Footsteps* visualizations, displayed field by field.

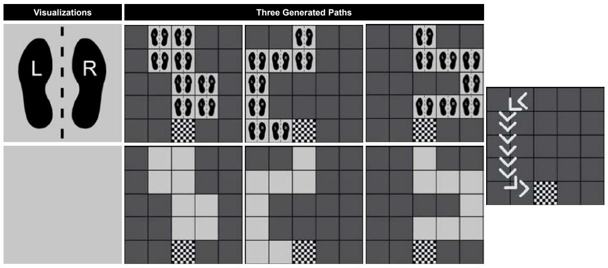

Figure 2: The top row displays the *Footsteps* visualization, including the three different paths. The bottom row shows the same paths with the *Empty Fields* visualization. The image on the right was shown at the end of each path to guide participants back to the starting field.

3.2 Procedure and Tasks

At the beginning of the study, participants were asked to sign an informed consent form. Following this, participants scanned a QR code and filled out a survey on demographic data and previous experiences. After a brief introduction to the study, participants were fitted with a MoCap suit, which included a beanie cap, jacket, pants, and foot wraps. Forty-one markers were attached to the suit according to the baseline template within the Motive [2] software from OptiTrack.

For the start of the first condition, participants were positioned at a visible starting field in the center of the first row of the grid. Depending on the condition, participants either wore a headset for the *AR* or *VR* environments, or did not wear it for the *RW* condition. Participants were instructed to step with both feet into each visible field, either sideways or forwards. The initial contact was measured, and then the next field was displayed. After completing a path, a visualization with arrows guided participants back to the starting field. This process was repeated twice for each condition, resulting in a total of three runs.

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

[2] https://optitrack.com/software/motive/

After each condition, participants completed the NASA TLX questionnaire to assess their perceived workload. This procedure was repeated for the remaining five conditions. At the end of the study, participants filled out a final questionnaire with questions about their preferred condition, reasons for their preferences, and ratings of various statements. Finally, participants received a certificate of participation. The study lasted approximately 45 minutes.

3.3 Apparatus

We used a MoCap system with ten PrimeX 13W cameras by OptiTrack to measure participants' foot angles and placement within the agility ladder. The cameras recorded at a frame rate of 240 Hz and were calibrated according to OptiTrack specifications, with a mean ray error of 1.255 mm and a mean wand error of 0.247 mm. OptiTrack's Motive software (version 3.0.3) was used for the creation of the participants' skeletons and the recording of all measurement data. The HMD was a Meta Quest 3 - 128 GB (90 Hz frame rate), equipped with an elite strap and battery to increase comfort and extend usage time. We used the game engine Unity [3] (version 2022.3.12f1) for the *AR* and *VR* visualization. To enhance realism and ensure participants could see their feet over the agility ladder in the AR environment without occlusion issues, we utilized the Meta XR All-in-One SDK [4] (version 67) package.

The software ran on a Windows 10 Pro system with an AMD Ryzen 5900X 12-core processor 3.70 GHz, a GeForce RTX 3700 graphics card, and 32 GB RAM. For the *RW* projection we mounted a Epson Projector EB 826WH to the trusses. The keystone distortion was manually corrected vertically and horizontally to match the agility ladder grid.

3.4 Measures and Data Analysis

Quantitative measurements of foot positioning success rate and foot angle, as well as subjective workload, were analyzed using inferential statistics with variance analyses. The statistical analysis was performed in the software R, utilizing the rstatix [5] package. Assessment of qualitative data from questionnaires was analyzed using thematic content analysis.

3.4.1 Quantitative Objective: Success Rate and Foot Rotation Angle

The quantitative data analysis was conducted using inferential statistics with a two-factorial repeated-measures (RM) Analysis of Variance (ANOVA). Foot placement measurements were registered after initial contact with the ground plane. A total of 6912 data points were recorded, 288 per participants, resulting in 16 data points per path (each foot with eight fields). The foot placement was documented for the toe and heel contact, in x and y direction (see Fig. 3). The rotation angle was measured for each foot separately, with inward rotation recorded as positive values and outward rotation as negative angles.

The success rate of foot positioning inside the grid was determined using a custom scoring system, specifically developed for this study to capture varying degrees of accuracy in foot placement. This method takes into account not only whether the foot is placed inside or outside the correct square, but also the alignment of the placement relative to the ideal positioning (i.e., correct half of the square). The reasoning for this approach is to allow a more detailed assessment of foot positioning, in contrast to the binary success/failure models commonly used.

Therefore, we defined the success rate of the foot positioning inside the grid as follows:

- 100% success: Both the heel and toe data points were inside the correct half of the field for the respective foot.
- 75% success: One data point (either heel or toe) was inside the correct half of the field, while the other was placed inside the square but not in the correct half of the field.
- 50% success: Both data points (heel and toe) were inside the square, but both were placed in the wrong half of the field; or one data point (either heel or toe) was inside the correct half of the field, while the other was placed outside the square (either outward,forward, or backward).
- 25% success: One data point (either heel or toe) was inside the square but not in the correct half of the field, while the other was placed outside the square (either outward,forward, or backward).
- 0% success: Both the heel and toe were placed outside the square (either outward,forward, or backward).

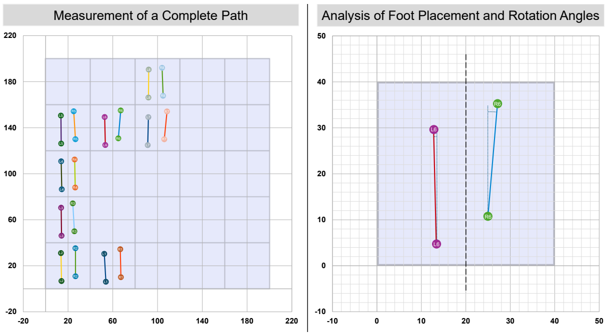

Figure 3: The illustration on the left shows the measurement of a complete path with 32 data points across eight fields. The figure on the right shows a selected field that displays the measurement of both feet (heel and toes) including their respective rotation angles.

3.4.2 Quantitative Subjective: Workload

The standardized questionnaire NASA TLX was used to assess the subjective workload after each condition. Participants rated their perceived workload on six scales (mental/physical/temporal demand, performance, effort, frustration level) from 0 to 20. The statistical analysis was performed using a two-factorial ANOVA.

3.4.3 Questionnaires: Quantitative and Qualitative Feedback

Post-study questionnaires included both closed-ended questions with multiple-choice answers and open-ended questions with free-text responses. Two questions using 5-point Likert scales were analyzed with descriptive statistics. Feedback from free-text responses was analyzed using an inductive content analysis [7]. One researcher independently coded the anonymized and transcribed data on a paragraph-by-paragraph level. A second researcher then cross-checked the dataset.

3.5 Participants

In total, 24 participants (6 female, 18 male) were recruited via mailing lists from our institution. The age range of participants was between 22 and 43 years (M = 25.5, SD = 4.28). All participants except one, who had a background in social science, had a technical background in engineering or computer science. Students were compensated with one credit point for their lecture.

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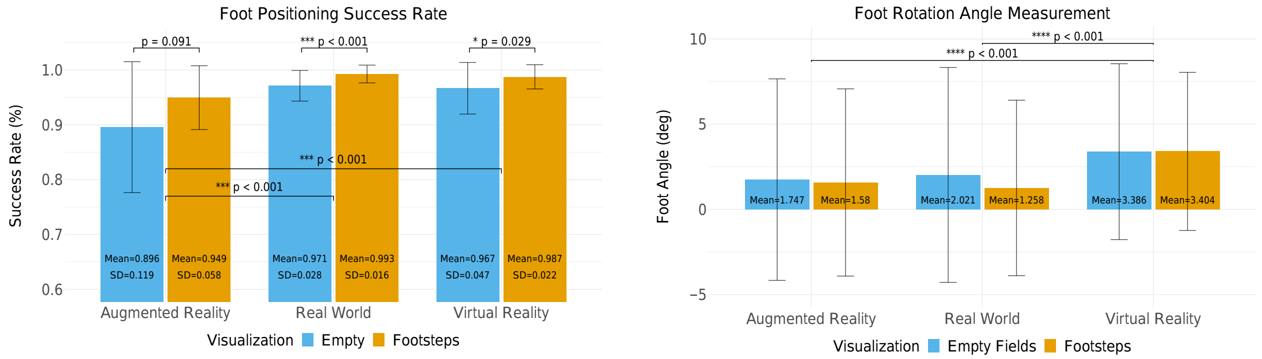
[3] https://unity.com/

[4] https://assetstore.unity.com/packages/package/269657

[5] https://rpkgs.datanovia.com/rstatix/



(a) Analysis of Foot Positioning Success Rates

(b) Analysis of Foot Rotation Angle Measurement

Figure 4: Bar chart with descriptive statistics, including means and standard deviations, for foot positioning success rates (a) and foot rotation angles (b) across three environments (AR, RW, and VR) and two visualization types: empty fields (blue) and footsteps (orange).

Since foot size may impact foot positioning accuracy during ladder training, shoe sizes were recorded, ranging from EU 36 to EU 46 (M = 41.92, SD = 2.64). A total of 10 participants wore glasses and two contact lenses. Eight participants stated to have previous experience with *AR* and/or *VR*. One participant had previous experience with agility ladder training or a similar coordination training method. Fourteen participants responded that they engaged in sports activities on an irregular basis, six participants reported one to two times per week, three participants three to four times per week, and one participant two to three times per week.

The study was conducted in accordance with the ethical standards and hygiene protocols for user studies as required by our institution, and received ethical clearance from the German Society for Nursing Science (No. 23-027).

4 RESULTS

This section includes the quantitative analysis of foot positioning success rates (Sec. 4.1), foot rotation angles (Sec. 4.2), perceived workload (Sec. 4.3), and feedback from questionnaires (Sec. 4.4), as well as the qualitative analysis of the post-study questionnaires (Sec. 4.5).

4.1 Quantitative Objective: Foot Positioning Success Rate

We conducted a two-factorial RM ANOVA on the success rates to investigate foot positioning performance. The Shapiro-Wilk test indicated that the data were not normally distributed (all conditions with $p \leq 0.00156$). An aligned rank transform (ART) ANOVA revealed a statistically significant main effect of the ENVIRONMENT, $F(2,115) = 23.157$, $p < 0.001$, $\eta_p^2 = 0.323$ (large effect size), and VISUALIZATION, $F(1,115) = 43.474$, $p < 0.001$, $\eta_p^2 = 0.311$ (large effect size), as well as a significant interaction effect between ENVIRONMENT and VISUALIZATION, $F(2,115) = 3.529$, $p = 0.033$, $\eta_p^2 = 0.068$ (medium effect size).

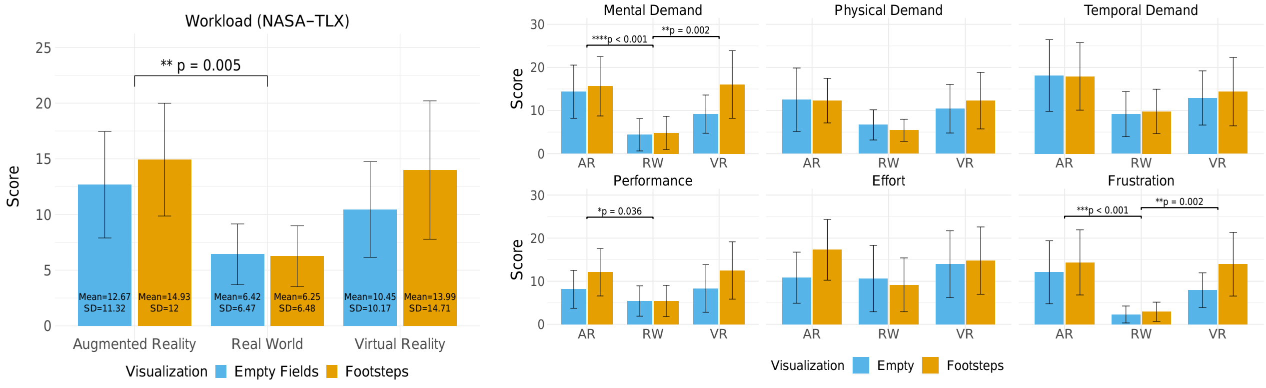
Pairwise post-hoc comparisons using the Wilcoxon signed-rank test showed significant effects between *AR* and *VR* ($p_{\text{adj}} < 0.001$), as well as *AR* and *RW* ($p_{\text{adj}} < 0.001$), but not between *RW* and *VR* ($p_{\text{adj}} = 0.604$). Comparison of *Empty Fields* and *Footsteps* showed a significant difference ($p_{\text{adj}} < 0.001$). The results indicated a significant effect on foot positioning success rates in the *AR* ENVIRONMENT, leading to lower success rates. In addition, the visualization of *Footsteps* led to higher success rates compared to *Empty Fields*, as shown in Fig. 4a.

4.2 Quantitative Objective: Foot Rotation Angle

The Shapiro-Wilk test indicated that the data were normally distributed, with p-values ranging from 0.252 to 0.768. A two factorial RM ANOVA with Greenhouse-Geisser correction revealed a statistically significant main effect of ENVIRONMENT, $F(1.58,36.29) = 25.159$, $p < 0.001$, $\eta_p^2 = 0.026$ (large effect size). However, VISUALIZATION showed no statistically significant main effect, $F(1,23) = 0.613$, $p = 0.441$, $\eta_p^2 = 0.522$, and no interaction effect between ENVIRONMENT and VISUALIZATION, $F(2,46) = 1.786$, $p = 0.179$, $\eta_p^2 = 0.072$. Post-hoc pairwise comparisons with Bonferroni correction revealed significant effects between *VR* and *RW*, as well as *VR* and *AR* ($p_{\text{adj}} < 0.001$ for both comparisons). However, no significant effect was found between *AR* and *RW* ($p_{\text{adj}} = 0.907$), nor between *Empty Fields* and *Footsteps* ($p_{\text{adj}} = 0.256$). The results indicated that *VR* had a significant effect on the foot rotation angle, which is documented in Fig. 4b including descriptive statistics.

4.3 Quantitative Subjective: Workload

To investigate the perceived workload for each task, we conducted a two-way ANOVA on the NASA-TLX scores. The Shapiro-Wilk test indicated that the TLX score data were not normally distributed across all conditions (p-values ranging from 0.002 to 0.026). An ART-ANOVA with Kenward-Roger corrected degrees of freedom revealed a significant main effect of ENVIRONMENT, $F(2,115) = 16.204$, $p < 0.001$, $\eta_p^2 = 0.474$ (large effect size). However, no statistically significant main effect was detected for VISUALIZATION, $F(1,115) = 2.047$, $p = 0.155$, $\eta_p^2 = 0.054$ (medium effect size), as well as no significant interaction effect was found between ENVIRONMENT and VISUALIZATION, $F(2,115) = 0.768$, $p = 0.466$, $\eta_p^2 = 0.041$ (small effect size). Post-hoc pairwise comparisons using the Wilcoxon signed-rank tests revealed a significant effect for *AR* and *RW* ($p_{\text{adj}} = 0.005$), but not between *AR* and *VR* ($p_{\text{adj}} = 0.327$), *RW* and *VR* ($p_{\text{adj}} = 0.12$), or *Empty Fields* and *Footsteps* ($p_{\text{adj}} = 0.591$), see Fig. 5a. Post-hoc pairwise comparisons of the six sub-scales are summarized in Fig. 5b. The statistically significant values of the six sub-scales are documented in Tab. 1. The results indicated that the perceived cognitive load in *AR* is significantly higher compared to *RW*, particularly in terms of mental demand, performance, and frustration levels. *VR* did not show a significant effect on overall workload, but it also led to higher mental demand and frustration levels compared to *RW*. In addition, the *Footsteps* visualization led to slightly higher workload scores in *AR* and *VR*, whereas in *RW*, the workload scores for *Footsteps* and *Empty Fields* were at the same level.



(a) Overall NASA-TLX Workload Score

(b) Six subscales of the NASA-TLX workload assessment

Figure 5: The left bar chart (a) shows the results of the overall workload score with descriptive statistics, and the right bar chart (b) includes the six subscales with highlighted significant effects.

Table 1: Post-hoc pairwise comparisons of the six NASA-TLX subscales across Environment and Visualization factors

	Environment				Visualization			
Subscales	$F(2,115)$	p	*Sig.*	η_p^2	$F(1,115)$	p	*Sig.*	η_p^2
Mental Demand	24.066	< 0.001	***	0.474	4.275	0.041	*	0.075
Physical Demand	5.307	0.006	*	0.401	—	—	—	—
Temporal Demand	6.234	0.003	**	0.484	—	—	—	—
Performance	7.405	< 0.001	***	0.417	3.396	0.068	.	0.142
Effort	3.978	0.021	*	0.368	—	—	—	—
Frustration	18.674	< 0.001	***	0.459	5.906	0.017	*	0.119

4.4 Questionnaires: Quantitative Feedback

Two statements from the post-study questionnaire on participant agreement were analyzed using descriptive statistics. The participants rated the statement: ”The use of MR (*AR*/*VR*) technology has increased my overall engagement with the training program”, using a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The responses were distributed as follows: ”neither agree nor disagree” (N=7), ”agree” (N=6), ”strongly agree” (N=4), ”disagree” (N=4), and ”strongly disagree” (N=3).

Additionally, participants rated the statement: ”The use of MR (*AR*/*VR*) technology has enhanced my ability to maintain correct foot positioning”, with the following responses: ”agree” (N=11), ”neither agree nor disagree” (N=6), ”strongly disagree” (N=4), and ”strongly agree” (N=3).

In total, 17 participants either agreed or were neutral about MR technology enhancing their engagement with the training program, while seven participants disagreed. Furthermore, 20 participants felt that MR technology supported them in maintaining better foot positioning during the exercises, while only four participants disagreed. These results indicated that the majority of participants found MR technology beneficial in supporting better foot positioning during exercises and enhancing engagement with the training program.

4.5 Questionnaires: Qualitative Feedback

The qualitative data from the post-study questionnaires were analyzed using thematic content analysis to identify patterns in the participants’ responses. Four main themes were identified: *Clarity in Visualization*; *Frustration and Technical Limitations*; *Immersion and Focus*, and *Usability and Discomfort*.

Clarity in Visualization:
Fifteen participants preferred *Footsteps* because it was ”easy to understand” (P2, P5, P11, P12), made it ”easier to place [the] foot correctly” (P15), provided ”clear instructions” (P9), and was ”more accurate” (P1, P19). In contrast, *Empty Fields* was chosen by nine participants for reasons such as ”less cognitive load” (P23), ”less decision fatigue” (P20), ”less that can be done wrong, resulting in less stress” (P21), ”you don’t have to take precise steps” (P14), and it was ”easy to go to the box however you want” (P4, P8).

Frustration and Technical Limitations:
Twelve participants rated *AR* as the most disliked environment for agility ladder training, because of a ”higher frustration” (P14, P21), as well as ”less identification with the environment ... [and] the legs were hard to see” (P21). Additionally, the visualization of the ”ladder [was] imperfect” (P4), and it was perceived as ”stressful, to see the offset between [the] real and virtual worlds” (P2). Some technical limitations of the AR passthrough function were also noted, including ”slight lens distortions at the outside border” (P23), ”blurry legs” (P19), a ”fake” appearance (P14), and that ”passthrough and overlay of foot positioning with the ladder could be better” (P15).

Immersion and Focus:
Thirteen participants preferred *VR* as the training ENVIRONMENT because it ”look[ed] very original, ... same as [the] real world” (P9), made them feel ”more focused” (P19), and was ”more immersive” (P15) while performing the tasks.

Usability and Discomfort:
Seven participants preferred the *RW* environment because they ”[did not] have to concentrate too much” (P14), there were ”no

heavy things on my head" (P17), and "no glasses had to be worn" (P1). Four participants chose the *AR* environment because it "was more pleasant than VR" (P8) and "really interesting and challenging" (P22). Five participants reported physical or mental discomfort after the experiment, including "tiredness" (P14), "headache" (P17), and "neck pain" (P20). Additionally, participants mentioned discomfort related to the headset, stating that "the glasses are quite heavy" (P21) and "the task was really easy and comfortable but only the headset is so heavy" (P12).

5 DISCUSSION

In an experimental user study with 24 participants, we investigated the effect of three ENVIRONMENTS (*AR*, *VR*, and *RW*) and two VISUALIZATIONS (*Empty Fields* and *Footsteps*) on foot positioning success rates, foot rotation angles, and the perceived workload during agility ladder training. Our findings showed that *AR* environments significantly lead to lower foot positioning success rates compared to *VR* and *RW*, as well as a higher perceived cognitive load. The qualitative feedback supports the quantitative data and provided more background on the reasons for participants' preferred conditions.

5.1 Environment: AR vs. VR vs. RW

Contrary to our expectations, the performance in *AR* was significantly worse, making it less suitable for this type of training. The qualitative feedback highlighted several technical challenges with using *AR* passthrough for ladder training. Although the Quest 3 is equipped with a depth sensor (utilizing an patterned light emitter in line projector form), the accuracy of the depth data remains inconsistent, with a noticeable lag. This lag occurs because the headset continuously measures the distance to objects in the environment to determine how virtual elements (e.g., the empty field visualization) should be displayed in relation to RW objects, such as the participant's feet. However, the measurement is not always precise, which can lead to visual inconsistencies, such as the fields occasionally appearing to sink into the ground or the participant's feet partially disappearing within the virtual fields. While specific details on the exact lag times are not provided by the manufacturer, these visual artifacts suggest that the delay in processing depth information is a contributing factor. Due to this limitation, the visible offset from the ground had to be manually adjusted, however, visualized information in *AR* was not perceived as fully immersive. In contrast, *VR* training appears to be more beneficial for agility ladder exercises with additional visual feedback. The qualitative feedback indicated a higher level of immersion in *VR*, which seemed to contribute to more focused task performance and a reduced workload. Results of success rates are comparable to the *RW* environment, although mental demand and frustration levels are slightly higher. Only the foot rotation angle was significantly different, with feet being inwardly rotated by approximately 3.4 degrees in the *VR* environment. This difference could be explained by the altered perception in *VR*.

5.2 Visualizations: Empty Fields vs. Footsteps

The results confirm our hypothesis that *Footsteps* visualizations lead to more accurate foot positioning across all three environments without significantly increasing the perceived workload. Nevertheless, in *AR* and *VR*, the visualization of *Footsteps* leads to a slightly higher workload (not significant). In *RW*, the difference between *Footsteps* and *Empty Fields* is highly significant for the success rate, however, there is no change in the perceived workload. In general, the use of *Footsteps* seems to be more useful for training that requires high placement accuracy. In contrast, the use of *Empty Fields* is perceived as less demanding, making it potentially more suitable for scenarios where basic positioning or overall movement patterns are the primary focus.

5.3 Implications for Interactive Feedback

Our findings that *VR* is appropriate for ladder training align with results from related work [19], which demonstrated the feasibility of using a *VR* HMD for this kind of training. However, our study goes further by demonstrating the potential of *VR* to improve foot positioning success rates through *Footsteps* visualizations, without increasing the cognitive load. The results indicate that *VR* performs similarly to *RW*, with the only significant difference being in foot rotation angles compared to the *RW* environment. For an enhanced immersive training environment, the potential for visual feedback in *VR* could be used to provide specific foot placement correction instructions.

In contrast, the use of *AR* passthrough is not appropriate for this type of training. Based on our findings, we identified several challenges in using *AR* passthrough for agility ladder training, such as lower resolution and occlusion issues. Our findings suggest that future immersive training environments should focus on enhancing visualizations to improve success rates and reduce overall workload. Beyond ladder training, *VR* foot position training could be beneficial for users recovering from injuries, allowing them to practice everyday movements at home. Active instructions delivered through visual feedback in *VR* environments would reduce the need for in-person coaching, making rehabilitation more accessible.

5.4 Limitations and Future Work

The study was conducted under laboratory conditions with a small sample size of healthy participants, which limited the generalizability of the results. The findings are specific to the video-see-through HMD (Meta Quest 3) and may not be applicable to optical-see-through HMDs. In general, the *AR* passthrough function varies between different HMDs and across various versions of the same device. The imprecise depth information can lead to an overlay of the visualization or grid pattern with the feet, which can only be manually adjusted but not fully corrected. Due to the limitations of *AR* video passthrough, we recommend *VR* training environments for future rehabilitation applications.

Future development of *VR* training environments should focus on incorporating active gait feedback on the accuracy of foot placement and rotation angles. By adding direct feedback on foot placement success, we expect a more beneficial training environment compared to the *RW*. Additionally, correction instructions for angular offset could help users adjust their foot placement, further enhancing the training effects. Furthermore, follow-up work should focus on testing the long-term effects of *VR* training with patients.

6 CONCLUSION

In a study with 24 participants, we compared three environments (*AR*, *VR*, and *RW*) and two visualizations (*Footsteps* and *Empty Fields*), demonstrating that *VR*-created training environments are comparable to *RW* settings. Our findings indicate that *VR* can offer significant benefits by incorporating visual feedback which is normally not possible in *RW* training. This visual feedback offers opportunities to improve training results, especially for tasks that require accuracy, such as foot positioning. For future implementations, challenges such as improving visualizations and addressing realism issues must be tackled to further enhance the user experience and ensure high user satisfaction. Despite these challenges, our study provides valuable insights into the growing field of immersive training applications for rehabilitation, highlighting the promise of *VR* as a tool to enhance rehabilitation outcomes.

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