Correct Foot Positioning in Virtual Reality through Visual Agility Ladder Training

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ABSTRACT

Incorrect gait patterns and foot positioning can lead to serious consequences for the entire musculoskeletal system of the human body. While previous work indicates that training with an agility ladder in immersive environments such as in virtual reality (VR) is helpful for training foot positioning using visual feedback, it remains unknown how the visual feedback affects the users' gait pattern. In an experimental user study (N=20) in VR, we compared the foot positioning success rate and the users' preferences using four different visualization techniques of an agility ladder (*footsteps*, *arrows*, *numbers*, *empty fields*). The quantitative results indicate that visualization of footsteps achieved the highest accuracy in correct foot positioning without increasing the workload in VR. This is in contrast to the qualitative feedback in which most of the participants were in favor of the empty field condition. We discuss the implications and limitations for future studies using agility ladder training in VR.

CCS CONCEPTS

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

KEYWORDS

virtual reality, agility ladder, visualization, foot positioning

MuC '23, September 03–06, 2023, Rapperswil, Switzerland

ACM ISBN 979-8-4007-0771-1/23/09…$15.00
https://doi.org/10.1145/3603555.3608558

ACM Reference Format:
Stefan Resch, Mustafa Rafati, Angela Altomare, Oumaima Raddi, Arso Tahmas, Valentin Schwind, and Diana Völz. 2023. Correct Foot Positioning in Virtual Reality through Visual Agility Ladder Training. In *Mensch und Computer 2023 (MuC '23), September 03–06, 2023, Rapperswil, Switzerland*. ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3603555.3608558

1 INTRODUCTION AND BACKGROUND

Foot deformities are a widespread condition that affects people of all ages around the world. These deformities can lead to chronic misalignment within the musculoskeletal system, often resulting in abnormal gait patterns [16, 18, 22]. Affected joints are also subjected to higher forces and moments, which is why patients are also increasingly suffering from pain [12]. These issues can impair everyday movement activities, hinders daily mobility, and lead to long-term health problems [14, 24]. In internal rotation gait (in-toeing) or external rotation gait (out-toeing), the foot axis is rotationally off-center and provides visible incorrect positioning of the feet. Finding effective ways to actively improve foot positioning is therefore highly important for patients. In the field of rehabilitation training, physical therapists use various exercises and techniques to train patients' coordination and gait [8, 17, 21].

To improve agility and motor skills, a so-called "agility ladder" or "coordination ladder" is often used in therapy, prevention, and rehabilitation sports (e.g. exercises after stroke or accidents) as well as in competitive and amateur sports [1, 11, 13]. Ladder training enables participants to train exercises with different movement sequences and to constantly increase the level of difficulty (e.g. different step sequences, increase the speed) [5]. The agility ladder, typically a physical apparatus composed of multiple square sections arranged in a linear or grid pattern, is navigated using specific footwork sequences [11]. During therapy or training sessions, various stepping patterns can be prescribed with the aim of traversing the ladder swiftly and accurately [4]. Potential errors, such as incorrect foot placement or stepping outside a designated square, are generally inconsequential to health and treatment outcomes.

The employment of immersive mixed reality (MR) technologies, encompassing both augmented reality (AR) and virtual reality (VR), holds significant potential for enhancing motivation and learning experience during training sessions [5, 13, 15]. One of the key advantages of training within these immersive environments is the ability to present additional information to participants while simultaneously controlling study parameters, tracking, and real-time data analysis of a participant's movements and engagement. The utilization of these technologies also facilitates a high level of customization such as dynamic adaption of the ladder size according to the feet or body properties. Thus, using immersive technologies is currently a growing area of research within the realms of sports and rehabilitation, catering to diverse target groups afflicted with various medical conditions [5, 19].

Improving the aspect of agility ladder training in immersive environments has also been subject in a number of studies [13, 15]. For example, Kosmalla et al. presented a study with 12 participants who tested two different visualizations (projection on the floor and on a screen) during walking ladder training to observe differences in participants' agility [13]. Using the *Illinois Agility Test (IAT)* [2, 10, 20], the agility was finally evaluated and showed that visualizations on the screen lead to better results [13]. A study by Lei et al. describes the use of ladder training with a full immersive VR head-mounted display (HMD) [15]. In this study, they compared agility ladder training in VR to the real world (RW), however, were not able to find differences between both tasks VR and RW highlighting the validity of the procedure immersive settings. This provided a first approach that an agility ladder is also suitable by using VR HMD for training purposes.

As previously mentioned, the foundation of the agility ladder on the ground, whether area-based [7] or row-based [6], serves as a visual guide for foot placement. The row-based ladder, in particular, facilitates the visual assessment of correct foot positioning, whether within or outside the designated squares. These squares act as visual reference points while training, enabling the execution of lateral steps outside the square and back in. However, it is currently unclear which visualizations can effectively assist participants in performing these exercises accurately. The insights gained from addressing this research gap could be beneficial for better rehabilitation training and independent use, serving the interests of both therapists and patients.

In this paper, we present the results of an experimental user study in VR involving 20 healthy participants to examine the impact of different visualizations on performance using a (virtual) agility ladder. Our findings suggest that footstep visualization enhances the success rate of agility ladder training compared to other visualization techniques. As footstep visualization indicates the rotatory foot alignment, participants are able to improve foot positioning without increasing their workload in VR. These results highlight the potential of VR in gait training but also underpin the need for further research to optimize the balance between training effectiveness and user workload.

2 METHOD

To understand the potential to enhance the effectiveness of agility ladder training in VR environments, we conducted an experimental user study investigating the effects of different visualization forms for correct foot positioning. The only independent within-subject variable VISUALIZATION comprises the levels *footsteps*, *arrows*, *numbers*, and *empty fields*. The hypothesis of our study is that visualization of footsteps helps to improve the alignment of the feet' position during the agility ladder task. During the study, participants navigated through a virtual ladder featuring various forms of visualization. Concurrently, their foot positioning was measured to evaluate the degree of improvement in positioning accuracy.

2.1 Visualizations

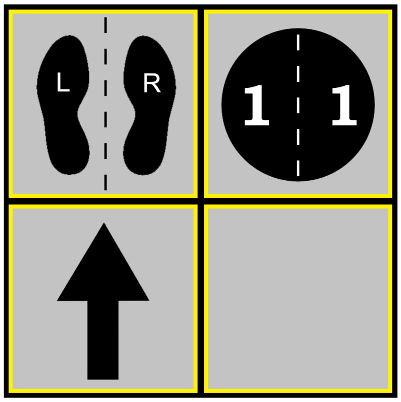
The user's intended path was visualized with one of four visualizations: *footsteps*, *arrows*, *numbers* and *empty fields*, as shown in Figure 1. The starting square was situated in the lower right corner of the grid, while the finish square is in the top left corner. This arrangement allows the participant to traverse a series of squares laterally in succession while moving forward. The movement was restricted to a square-by-square basis and can only be executed in a forward or sideways direction. Upon entering a square with both feet, it becomes highlighted, and the subsequent visualization in the next square illuminates. Each visualization method offered a unique approach to guiding the user, and understanding their individual impacts can help to optimize the design of VR-based agility ladder training programs.

2.2 Apparatus

In the virtual environment, participants saw through the HMD a virtual replica of the real space they are standing in. On the floor of the (virtual) laboratory was an agility ladder area with 35 fields in a 7 x 5 grid. Each field has a size of 40 x 40 centimeters (length x width), comparable to a standardized physical ladder. An OptiTrack motion capture system with 16 cameras (PrimeX 13W) was used to track the motion sequences of the participant and render their virtual avatar. The system was calibrated according to OptiTrack specifications, resulting in the following precision: mean ray error: 0.98 mm, mean wand error: 0.23 mm. The resolution of the cameras was 240 Hz. Participants wore an OptiTrack tracking suit (consisting of pants, jacket, and gloves) for the entire study.

To track the whole body movement and the HMD, 49 markers were attached to the participants (template: baseline and passive fingers). To enable natural walking in the lab, all participants wore the same thin black socks, which were also provided with markers. Participants had to adopt a T-pose to create and calibrate the skeleton in OptiTrack. The virtual avatar was created with DAZ3D[1] and animated using the OptiTrack[2] skeleton. Motion data was recorded and live-tracked in Motive 3.0.1 software. The Unity 3D engine (version 2020.3.41f1) was used to render the VR environment. An HTC Vive Pro 2 with 90 frames per second (FPS) was used as the target frame rate for the HMD. Four HTC lighthouse stations were placed in the corners of the room to ensure correct tracking.

[1]https://www.daz3d.com/
[2]https://optitrack.com/



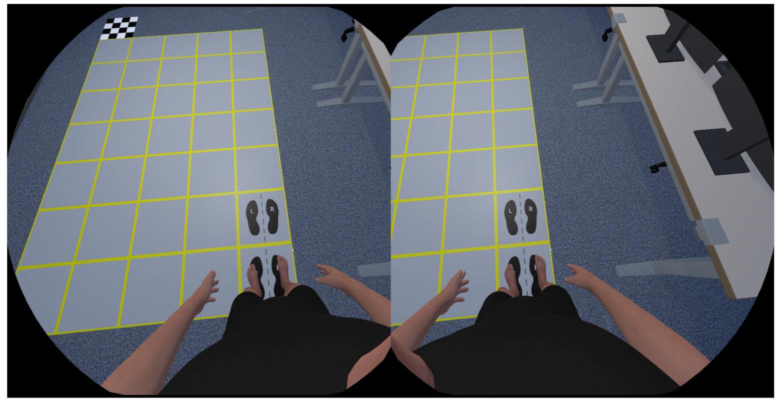


Figure 1: The four visualization techniques (footsteps, number, arrow and empty field) displayed to the participants during the respective conditions (left) and the view of the participant during the laboratory study (right)

2.3 Measures

To assess the accuracy of foot positioning, we used the success rate capturing the number of correct foot placements in the marked quadrant fields. For the analysis of the foot positioning, the raw data of the markers were extracted from the Motive software by OptiTrack. For evaluation purposes, the classification of the "success rate" is defined as follows:

- No foot is positioned correctly (false step: value = 0)
- Both feet are inside the field (correct step: value = 1)

The success rate was calculated for each condition by dividing the number of correctly entered fields ($n_{\text{correct steps}}$) by the total number of fields to be entered ($n_{\text{total steps}}$). In the five repetition runs of each condition, a total of 61 marked fields are run through, which are then evaluated for correct foot position. The result can be expressed as a percentage and represents the proportion of correctly entered fields out of the total number of fields.

In addition, we assessed the perceived workload using the NASA raw taskload index (RTLX) with six items [9]. To assess their workload, participants completed a digital questionnaire implemented in VR after each condition as recommended by previous work [23].

Qualitative feedback was recorded through questionnaires before and after the study. Prior the study, all participants were asked about their demographics, existing experience with agility ladder, VR, and known foot deformities. After the study, a questionnaire was used to determine which visualization was preferred and why. The anonymized data was evaluated by deductive thematic analysis [3]. Two researchers coded and independently reviewed the recorded data.

2.4 Procedure and Tasks

After signing the informed consent, participants were introduced to agility ladder training and the details of the procedure. All participants were surveyed for their demographic data, as well as previous experience with agility ladders, VR experience, and any issues related to poor body posture. Next, participants were equipped with the motion capture suit and other HMD to track and visualize their body movements as an avatar in the virtual environment. At the beginning of the study, the participants were introduced to the VR environment and placed on a visible designated starting field in the virtual laboratory. To avoid any collisions with the surroundings the dimensions of the virtual lab matched the real one. Participants were instructed to pass the agility ladder through a predetermined path, guided by illuminated fields. Each marked field must be visibly entered with both feet, only then the next field lights up.

There was no time limit for passing through the marked fields. Five runs were performed for all of the four visualization forms, reaching the finish field at the end of the agility ladder marking the end of one run. The visualizations were counterbalanced in a 4 × 4 Latin square to counter-balance any order effects. At the end of the study, participants completed a final questionnaire and provided information about their preferred task based on their experience in the study. The study took approximately 30 minutes per participant.

2.5 Participants

We recruited 20 participants (4 female, 16 male) from multiple computer science courses at our institution for the study. All student participants attended voluntarily and received credit points for the lecture unit. Participants' age ranged from 21 to 42 years (M = 25.15, SD = 5.02). Twelve participants stated to have any previous experience with VR devices. One participant has previous experience with a physical agility ladder. Participants were given the freedom to pause or discontinue the study at any time. At the end of the study, two participants reported mild complaints of cybersickness, which did not necessitate pausing or terminating the study. All participants were included in the evaluation. The study received ethical clearance according to the regulations and hygiene protocols for user studies as required by our institution.

3 RESULTS

The collected data on success rate and workload are assessed quantitatively. For evaluation purposes, we use inferential statistics with variance analyses. In addition, a qualitative analysis of the questionnaires is conducted by thematic analysis.

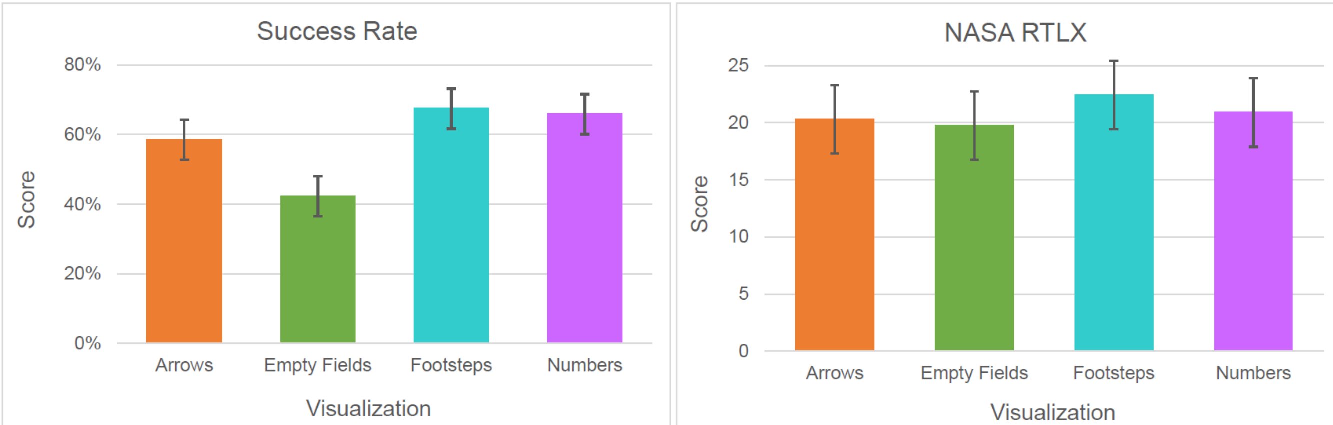


Figure 2: Bar chart with mean values and standard deviations of the success rate (left) and RTLX workload (right) for the four visualization methods

3.1 Quantitative Results

3.1.1 Objective: Success Rate. To investigate the effect on the foot positioning of the participants, we performed a one-way repeated-measures (RM) ANOVA on the success rate. One-way RM ANOVA showed a significant effect of the four VISUALIZATIONS on the success rate, $F(3, 57) = 28.032$, $p < 0.001$, $\eta_p^2 = 0.596$ (large effect size). Pairwise post hoc comparison using Bonferroni-corrected t-tests revealed significant differences between *empty fields* and *arrows* ($p < .001$), *empty fields* and *footsteps* ($p < .001$), *empty fields* and *numbers* ($p < .001$), but not between other conditions (all with $p > .068$). Results showed that the highest success rate of correct foot positioning was achieved for the visualization *footsteps* with 67.5% ($M = 0.675$, $SD = 0.144$), see Figure 2. The visualization *numbers* is close behind, with an average success rate of 65.9% ($M = 0.659$, $SD = 0.130$). The visualization *arrows* achieved an average success rate of 58.6% ($M = 0.586$, $SD = 0.120$) and *empty fields* has the lowest average success rate with 42.3% ($M = 0.423$, $SD = 0.165$).

3.1.2 Subjective: Workload. Shapiro-Wilk's normality tests indicated that the mean scores were normally distributed (all conditions with $p \geq 0.05$). To investigate which visualization causes a higher workload in VR, we performed a one-way RM ANOVA on the RTLX scores. There were no significant effects, neither on the overall workload, $F(3, 57) = 1.532$, $p = 0.216$, $\eta_p^2 = 0.075$, nor on its sub-scales (mental, physical, temporal, performance, effort, and frustration; all with $p > 0.09$). The highest workload was detected for the visualization *footsteps* with a mean value of 22.45 ($SD = 6.36$), see Figure 2. It is followed by visualization *numbers* ($M = 20.90$, $SD = 7.66$), *arrows* ($M = 20.30$, $SD = 6.34$) and at least *empty fields* with a mean of 19.75 ($SD = 7.15$), but there was no significant increase in workload found overall.

3.2 Qualitative Results

After the last condition, participants were given a final questionnaire to find out which condition was preferred for agility leader training and why. Evaluation of the qualitative feedback was performed by thematic analysis (themes: preferred condition, reason for preference, general feedback on the study). The recorded data were transcribed and coded independently by two researchers. The data were analyzed paragraph-wise and finally cross-checked. In the post-survey, eleven participants indicated the visualization of *empty fields* as their preferred condition. This condition provided "less effort" (P2), "least distraction" (P17), and enabled "better concentration" (P4). Four participants mentioned the visualization of *arrows* as the preferred condition because it "showed the direction" (P9) and it was "easy to follow" (P18). Three participants preferred the visualization of *footsteps* because it was "easy to position the feet" (P3). One participant preferred visualization of *numbers* and one participant did not specify any preferences. In general feedback on the Study, some participants reported that they found the visualizations "very motivating" (P10, P15, P17) for training in VR.

4 DISCUSSION

An experimental user study with 20 participants was conducted to investigate the influence of four visualizations on the accuracy of foot positioning in a virtual ladder. Evaluation of quantitative objective data (success rate) confirmed the hypothesis that the visualization of *footsteps* leads to more accurate positioning (average 67.5% success rate). Furthermore, no significant increase in workload was found in the visualization of *footsteps*. The qualitative questionnaire showed that 55% of the participants prefer the *empty fields*, as these visualizations require less concentration. This result is also reflected in the determined one-way RM ANOVA on the RTLX workload score (*empty fields*: mean value of 19.75), as it leads to the lowest workload. Overall, no significant difference in workload was found between all visualizations. However, the visualization of *empty fields* leads to the lowest success rate (average 42.3%) in foot positioning. The evaluation provides a first indication that more accurate foot positioning leads to a higher workload through the visualizations. In conclusion, we found that the virtual ladder with *footsteps* as a visualization method can be very effective in ensuring proper foot positioning. These findings serve as a first step in improving foot positioning during VR ladder training and should serve as a basis for further follow-up work. The generalizability of the results is subject to the limitation of a small sample size and uneven gender distribution. Therefore, the effects of the visualizations cannot be unambiguously assessed for both genders. In addition, the study was conducted with healthy young participants, so the results can not be inferred for the entire population. Another limitation is that only foot placement accuracy was assessed in the study tasks. Other factors affecting mobility performance were not measured and evaluated. In a follow-up study, further investigations on visual feedback during immersive ladder training will be conducted. In particular, we want to investigate the effects of virtual ladder training compared to ladder training under real-world conditions. Furthermore, the influence on people with foot deformities will be tested.

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