The Eyes Have It: Visual Feedback Methods to Make Walking in Immersive Virtual Reality More Accessible for People With Mobility Impairments While Utilizing Head-Mounted Displays

M. Rasel Mahmud
Computer Science
The University of Texas at San Antonio
San Antonio, Texas, USA
mrasel.mahmud@my.utsa.edu

Alberto Cordova
Kinesiology
The University of Texas at San Antonio
San Antonio, Texas, USA
Alberto.Cordova@utsa.edu

John Quarles
Computer Science
The University of Texas at San Antonio
San Antonio, Texas, USA
John.Quarles@utsa.edu

ABSTRACT

The use of Head-Mounted Displays (HMDs) in Virtual Reality (VR) can cause gait disturbance problems for users because they are unable to see the real world while in VR. This is particularly challenging for individuals with mobility impairments who rely heavily on visual cues to maintain balance. The limited research that has been conducted on this issue has not focused on ways to solve it. IN this study, we investigated how different visual feedback methods affect walking patterns (i.e., gait) in VR. The study involved 50 participants, including 25 individuals with mobility impairments due to multiple sclerosis and 25 without mobility impairments. The participants completed timed walking tasks in both the real world and in VR environments that included various types of visual feedback, such as spatial, static, and rhythmic. The results showed that static and rhythmic visual feedback significantly improved gait performance in VR for people with mobility impairments compared to no visual feedback in VR. The results will help to make more accessible virtual environments for people with mobility impairments.

CCS CONCEPTS

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

KEYWORDS

Virtual reality, visual feedback, gait disturbances, accessibility, usability, gait improvement, Head-Mounted Displays

ACM Reference Format:
M. Rasel Mahmud, Alberto Cordova, and John Quarles. 2023. The Eyes Have It: Visual Feedback Methods to Make Walking in Immersive Virtual Reality More Accessible for People With Mobility Impairments While Utilizing Head-Mounted Displays. In *The 25th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '23), October 22–25, 2023, New York, NY, USA.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3597638.3608406

ASSETS '23, October 22–25, 2023, New York, NY, USA

ACM ISBN 979-8-4007-0220-4/23/10.
https://doi.org/10.1145/3597638.3608406

1 INTRODUCTION

Immersive Virtual reality (VR) technology using head-mounted displays (HMDs) has many applications, including education, physical fitness, rehabilitation, and entertainment. However, previous research has demonstrated that HMDs may negatively impact the walking patterns of users, as they obstruct peripheral vision. This is a major accessibility issue for individuals with mobility impairments (MI) [11, 14, 38], because VR exacerbates their balance issues, potentially causing falls or injuries. Unfortunately, VR research and development have largely overlooked the needs of these individuals, resulting in exclusive and inaccessible experiences [3]. Despite these challenges, little research has been carried out to address these issues.

VR technologies have previously been used for gait rehabilitation. However, previous research has shown that immersive VR environments using HMDs decreased users' gait stability, leading to increased near falls and stumbles [47]. Consequently, HMDs are not widely used in rehabilitation programs. Instead, projectors and large screens serve as the predominant display medium for these programs. However, prior research indicates that HMDs are more immersive than projectors and that users may feel a greater sense of presence [2]. Theoretically, HMDs could more effectively engage participants. Therefore, it is necessary to resolve the gait disturbance issues of users while wearing HMDs.

To tackle these problems, our study explores the potential of various visual methods in immersive VR environments for individuals with and without MI. Participants completed walking tasks utilizing GAITRite, to quantitatively analyze gait parameters. Our study aimed to improve the accessibility of HMD-based immersive VR using different kinds of feedback and assess its impact on gait performance in VR. Our major contributions include the following:

- We investigated three visual feedback techniques (spatial, static, and rhythmic) for gait improvement in VR. A few studies investigated only one kind of visual feedback during standing balance [10]. To our knowledge, no study has analyzed and compared three different visual techniques in immersive VR for gait improvement.
- We recruited participants with mobility issues because of Multiple Sclerosis (MS), and participants without mobility issues. We had 50 people in our study (25 with MI due to MS and 25 without MI).

2 BACKGROUND

2.1 Gait Disturbances in Virtual Reality

If there are deviations from a person's baseline walking or gait, then those are referred to as gait disturbances. Gait disturbances include decreased walking velocity and cadence, asymmetrical step and stride lengths, increased step cycle, and swing times [19]. In previous research, virtual reality caused instability and gait disturbances [28]. In addition, the use of HMDs may cause individuals to lose their balance due to end-to-end latency. People can not see real world while using HMDs, which contribute to gait disturbances [29, 41]. In addition, long-term VR exposure led to postural instability [32]. Walking in a virtual environment (VE) can result in gait instability due to postural and gait instabilities [16]. In addition, Riem et al. [35] discovered that VR significantly altered stride lengths compared to baseline settings ($p < .05$). In other studies [42], VR has also been associated with imbalance and gait disturbances. Horsak et al. [18] analyzed the disparities in gait of 21 participants (male: 9, female: 12, mean age: 37.62 years) while walking in an HMD-based VE. Their findings revealed that the HMD-based VE decreased walking pace by 7.3%. Canessa et al. compared real-world walking with immersive VR walking while using an HMD in their study [5]. Based on their findings, they determined that walking speed was considerably ($p < .05$) slower in immersive VR than in the real world. Martelli et al. [28] used a VR HMD with visual feedback to examine how the gaits of healthy young adults are affected while walking in an immersive virtual environment. Twelve young and healthy adults walked for six minutes on a path in four distinct environments. Due to the disruption of the visual field, stride length, breadth, and variability were diminished. Despite these gait disturbance issues in VR, there have been few attempts to address them in the past. Therefore, we focused on these gait disturbance issues to improve the immersive VR walking experience.

2.2 Gait Improvement After VR Intervention Using Visual Feedback

Higher walking velocity, cadence, step length, stride length, and shorter step time, cycle time, and swing time are indicative of enhanced gait performance [45]. Walker et al. [46] designed a low-cost VR system in enhancing mobility and balance in seven post-stroke patients. Participants were able to experience traveling along a city street using a television screen while using the treadmill. Position sensors affixed to the head were used to capture postural feedback. During the investigation, all participants wore an overhead suspension harness. Participants in the study were within a year of their stroke and had previously received conventional rehabilitation, but they also had significant gait issues. According to their findings, there was a significant ($p < .05$) improvement in balance, walking velocity, and gait functionality following the study. They reported a 10 % increase in Berg Balance Scale (BBS) scores, a 38 % increase in walking speed, and a 30 % increase in Functional Gait Assessment (FGA) scores.

Janeh et al. [20] examine the efficacy of a VR-based gait manipulation approach designed to modify stride length to attain gait symmetry. Using visual and proprioceptive cues, they were able to compare natural gait to walking conditions while engaging in VR-based gait activities. VR gait activities increased step width and swing time compared to natural gait. Moreover, Janeh et al. reported that experiencing VR may enhance the gait performance of individuals with neurological disorders. As a consequence of their observations, they emphasized the significance of incorporating virtual walking techniques into rehabilitation.

The gait rehabilitation approaches did not, however, employ immersive VR techniques with HMDs due to gait disturbance issues. In our study, we evaluated visual techniques to solve the issues.

2.3 Gait Improvement Associated With HMDs for Participants With MI

Winter et al. [48] explored an immersive, semi-immersive, and no-VR environment on treadmill training walking. The participants began their treadmill training without VR. Participants in the semi-immersive VR condition used a monitor. Participants utilized HMDs to experience the same VR scenario in immersive VR condition. Immersive VR during gait rehabilitation increased walking velocity significantly ($p < .001$) more than semi-immersive VR and no VR conditions for both participant groups. The VR conditions did not induce cybersickness or a heart rate increase significantly.

Additionally, Guo et al. [15] investigated the effect of VEs on gait in participants with and without MI using HMDs. For participants with MI, walking velocity, step length, and stride length improved compared to the participants without MI. Other gait parameters were not substantially different between participants with and without MI. However, the HMD in their study had the periphery unblocked, which may have made the imbalance effects less pronounced.

Ferdous et al. [11] explored visual feedback to improve postural stability for participants with MS. They found balance improvement for participants with MI in their study during standing balance activities. However, they did not examine the effect of visual feedback on walking patterns. The impact of visual feedback on walking in immersive VR with HMDs has, therefore, received insufficient attention. Prior studies concentrated on individuals without MI [9, 17, 24, 36, 39]. We investigated the effect of visual feedback on walking in participants with and without MI using immersive VR with HMDs.

To summarize, visual feedback has been largely used in the non-immersive environment using a mirror or desktop monitor (e.g., in the field of rehabilitation). However, visual feedback methods in immersive VR for gait improvement have rarely been considered. Thus, we investigated the effect of different visual feedback methods on gait in immersive VR.

3 METHODS

3.1 Study Conditions

Figure 1 shows the various visual feedback conditions investigated in our study. We wanted to see if the static method used in [40] works for increasing gait performance in immersive VR. We recruited participants with MS who had less physical functioning and were prone to cybersickness with a lot of visual signals [30]. Thus, the texture in [40] was suitable for participants with MS as it was a simple '+' surrounded by four L-shaped boundaries. That is why we decided to select the texture in [40] over other textures. We also investigated the effects of rhythmic and spatial conditions, which were not explored in prior works.

3.1.1 Non-VR Baseline: We measured participants' gait while walking on the real-world GAITRite without any visual feedback for this condition.

3.1.2 VR Baseline: Without any additional visual feedback, participants completed the virtual walking tasks. However, they could still see the VE the entire time. We utilized this to assess how the gait of participants is affected in immersive VR without any additional visual feedback.

3.1.3 Spatial Visual Feedback: In order to maintain uninterrupted communication within the VR environment, our goal was to utilize a texture in the VE that minimizes obstruction to the VE. As a result, our texture was composed of five compact static frames, featuring a central cross-hair and four L-shaped frames situated in each of the four corners. (Fig. 1(A)). The texture was attached to the front wall and did not move with the participant's view. The texture was sufficiently large to remain within the participants' field of view, even if they moved their heads slightly to the left or right. We were inspired by a previous study [22] in which the researchers examined the visual effect of a texture (a '+' sign in front of the participant) and optic flow on the participants' balance. Due to the fact that the feedback in their study was a combination of spatial and optic flow, it was unclear to what extent spatial feedback affected balance. Also, their study was in a real-world environment and investigated the balance of the participants. However, we investigated the effect of spatial visual feedback on the gait of the participants in immersive VR using HMDs which was not the case in the previous study.

(A) Spatial: The texture was fixed to the front wall and did not move with the participant's view.

(B) Static: Texture tilted to left when participant's head tilted to left. The same happened for the "Rhythmic condition" except the texture was shown at every 1-second interval.

(C) Static: Texture tilted to right when participant's head tilted to right. The same happened for "Rhythmic condition" except the texture was shown at every 1-second interval.

Figure 1: Diffferent visual feedback conditions used during walking in the virtual environment

3.1.4 Static Visual Feedback: We utilized the same virtual static frame texture from the spatial condition. The texture was in the exact same location and dimension. This time, however, the texture moved with the participant's view. For example, when the participant's head tilted to the left or right, the texture also tilted to the left (Fig. 1(B)) or right (Fig. 1 (C)) to provide feedback to the participants that he was moving to his left or right. It was a form of a heads-up display resembling the reticle in popular VR games. We followed a prior work by [40] to implement this. However, no prior study investigated this kind of visual feedback to solve the gait disturbance issues in immersive VR.

3.1.5 Rhythmic Visual Feedback: This condition was similar to the previous static rest frame condition, except that the virtual static frame was displayed every one-second interval instead of continuously. We chose a one-second interval for rhythmic conditions because it was effective in previous research on auditory feedback for maintaining balance in VR [25]. Previous research in VR [25] and non-VR [13] environments indicated that rhythmic auditory rhythms contributed to enhancing balance and gait. This motivated us to investigate rhythmic visual feedback, which was not explored before.

3.2 HYPOTHESES

This study investigated the effects of spatial, static, and rhythmic visual feedback conditions on gait in an immersive virtual environment. These approaches had never been directly compared to each other before. We were influenced by prior research on gait disturbances in VR, visual feedback in the non-VR and VR environments, and three forms of audio and vibrotactile feedback (spatial, static, and rhythmic) in VR [25, 27] and non-VR contexts [7, 12, 13, 37, 44]. In addition, the following hypotheses were investigated based on prior research:

H1: Unlike non-VR baseline without visual feedback, VR baseline without visual feedback will result in gait disturbances.

H2: Spatial, static, and rhythmic visual methods will be effective in enhancing gait performance significantly more than the VR baseline without visual feedback conditions.

H3: Static and rhythmic visual feedback will improve gait metrics more than spatial visual feedback.

H4: While experiencing visual feedback in VR, participants with MI will experience greater gait improvement (e.g., walking velocity) than those without MI.

3.3 System Description

3.3.1 Computers, VR Equipment, and Software: We developed the virtual environments using Unity3D. Our experiment utilized the wireless HTC Vive Pro eye HMD, which had a refresh rate of 90 Hz, a 110-degree field of view, and a pixel resolution of 2160 x 1200. We used a computer with an NVIDIA GeForce RTX 2080 graphics card, an Intel Core i7 processor (4.20 GHz), and 32 GB DDR3 RAM.

3.3.2 Safety Equipment: For the safety of our participants, we utilized a suspension walking system from Kaye Products Inc. that included a body harness, thigh cuffs, and a suspension walker.

3.3.3 Gait Analysis: Using the GAITRite walkway system, we collected participants' gait parameters. The system consists of a 12-foot portable pressure sensor pad capable of measuring participants' gait metrics during a walking test. The GAITRite walkway system is able to collect both spatial and temporal gait data from participants.

3.3.4 Environment: During the investigation, a controlled laboratory environment was utilized (>600 square feet). In order to minimize noise and any other disturbances from the adjacent environment, the experimenter and the participant were allowed inside the room. The walking task environments in the real world and in VR have been shown in Figure 2.

Figure 2: Timed walking task: real environment (left) and virtual environment (right)

3.4 Participants, Selection Criteria, and Screening Process

Based on the study design and correlations found in previous studies [25, 26], we conducted a power analysis with a =.05, at 80% power, and an expected medium (.5) effect, which indicated that 44 participants will be required. To make up for any potential withdrawals, we recruited 50 participants from the local area. 25 people (male: 12; female: 13; age range: 40-50) were affected by MS-induced MI. The remaining 25 people (male: 12; female: 13; age range: 40-50) did not have MI, or MS, and were comparable to the MI group in terms of age, weight, and height. 34.1% participants with MI were White, 33.4% percent were Hispanic, and 32.5% were Black. There were 33.4% White, 33.3% Hispanic, and 33.3% African Americans in the without MI group. Table 1 displays the participants details for those with and without MI. Each person could walk without assistance. We recruited people from MS support organizations, rehabilitation centers, hospitals, and local communities. The primary recruitment methods were telephone calls, email lists, websites, and flyers.

Table 1: Participants details for both groups

Participant Group	Participants		Age (years)		Height (cm)		Weight (kg)	
	Male	Female	Mean	SD	Mean	SD	Mean	SD
MI	12	13	45.3	5.0	163.97	4.32	78.19	4.99
Without MI	12	13	44.87	4.6	163.74	4.18	79.03	4.86

Screening Procedure: First, we conducted a phone interview with each potential participant to determine their eligibility for this study. To assess their cognitive abilities, for example, we asked them a few simple queries, such as the year and date, as well as demographic information. Those who labored to comprehend the queries or lacked English proficiency were not selected. We then inquired as to the causes of their mobility impairment issues. In addition, we ensured that the participants in both categories were comparable in age, height, and weight. Participants who required assistance to stand or who were taking medications to improve their mobility impairment issues were excluded from the study.

3.5 Study Procedures

Institutional Review Board (IRB) at The University of Texas at San Antonio approved the study. Participants performed a COVID-19 symptom screening questionnaire at the beginning. We informed the study procedure to the participants, and their consent was obtained.

3.5.1 Pre-Study Questionnaires. Participants completed an Activities-specific Balance Confidence (ABC) form [34] and an SSQ questionnaire [21] initially. Participants were required to remove any footwear that could impede the GAITRite apparatus.

3.5.2 Real World Walking. A GAITRite walkway was used to measure gait metrics in this investigation. Participants were attached to safety harnesses. Then they started walking on the GAITRite with their comfortable speed. In addition, that had to take 180-degree turns at both ends. Participants step off the platform between trials, as the system cannot assess turns accurately. Three timed walking trials [43] were conducted for each participant, which were measured by the GAITRite software.

Figure 3: Comparison between real environment walking (left) and virtual environment walking (right) for the timed walking task.

3.5.3 Virtual Environment Walking. People walked on the virtual GAITRite using HMDs, which was overlaid on the physical GAITRite. HMDs were used to observe the VE and visual feedback. There were three trials for all visual conditions (e.g., spatial, static, and rhythmic) and a no-visual in VR condition. All study participants experienced the five conditions in a counterbalanced order. They used the same harness as in the real environment. Figure 3 depicts a comparison of the participants' walking in real and virtual environments.

3.5.4 Post-Study Questionnaires. Participants completed the same SSQ form as well as a demographic form at the end. All participants were paid $30/hour compensation and a parking validation permit.

4 METRICS

4.1 Gait Metrics

In our study, we investigated the following gait metrics:
- *Walking Velocity*: The distance traveled (cm) divided by ambulation time (sec).

- *Cadence*: The number of steps taken per minute.
- *Step Time*: The amount of time (sec) between the initial contact points of the opposite foot.
- *Step Length*: The distance (cm) between the centers of the heels of two consecutive steps taken by opposing feet.
- *Cycle Time*: The time (sec) between the initial contact points of the same foot's two consecutive steps.
- *Stride Length*: The distance (cm) between the steps of the same foot.
- *Swing Time*: The time (sec) between a foot's final contact point and its initial contact point.
- *Stance Time*: The time (sec) between the initial and final contact points of a single footstep.
- *Single Support Time*: This is the time (sec) between the final contact of the current footfall and the first contact of the following footfall of the same foot.
- *Double Support Time*: The time (sec) when both feet are on the ground.
- *Base of Support*: The width between one foot and the progression line of the opposing footstep.
- *Toe-In/Toe-Out*: The angle (degrees) between the progression line and the footprint's midline.

Relationship Between Gait Metrics: Walking velocity is the most important gait metric, as all other gait metrics are dependent on it. Gait disturbance occurs with a decrease in cadence, step length, and stride length and with an increase in step time, cycle time, and swing time, resulting in a decrease in walking velocity. Gait improvement occurs when cadence, step length, and stride length increase while step time, cycle time, and swing time decrease, resulting in an increase in walking velocity. The GAITRite manual provides additional information on gait metrics, their relationships, and measurements [1].

4.2 Activities-specific Balance Confidence (ABC) Scale

It was used to evaluate the balance, mobility, and physical functionality of the participants. This questionnaire uses sixteen items to determine whether an individual is capable of conducting daily tasks without losing balance [34]. Participants rated their confidence for a specific activity on a scale ranging from 0% (not confident) to 100% (most confident). The ABC Scale scores are computed by dividing the total number of ratings by 16. Below 50 on the ABC scale indicates limited functioning. In addition, scores between 50 and 80 on the ABC indicate moderate levels of functioning, and if the score is above 80, then that is considered a high level of functioning.

4.3 Simulator Sickness Questionnaire (SSQ)

Using the Simulator Sickness Questionnaire (SSQ) [21], the cybersickness of the participants due to exposure to a virtual environment was evaluated. The SSQ assesses participants' physical discomfort due to cybersickness using 16 symptoms organized into three distinct categories (disorientation, vertigo, and oculomotor disturbance).

5 STATISTICAL ANALYSIS

For each gait metric examined, the Shapiro-Wilk test (p >.05) and histograms revealed data normality for both participants with and without MI were normally distributed. Then, we conducted a $2x5$ mixed-model ANOVA in order to identify any significant differences between study conditions where participants with and without MI are two between-subject factors and study conditions (non-VR baseline, VR baseline, spatial, static, and rhythmic) are five within-subject factors. For post-hoc analysis, t-tests were conducted to determine the specific differences between the two study conditions. For cybersickness analysis, we also conducted t-tests for both groups. In addition, we compared the ABC scores of both participant groups using t-tests to determine the difference in participants' physical ability. We also applied Bonferroni corrections for multiple comparisons.

6 RESULTS

Among the twelve gait metrics studied, three gait metrics (walking velocity, step length, and stride length) improved significantly under static and rhythmic visual feedback conditions, whereas the remaining nine gait metrics did not significantly improve for the MI group. Gait metrics also varied significantly based on the conditions of visual feedback. We noticed no significant difference for without MI group. In addition, data for both the left and right legs were evaluated. There was no statistically significant difference between the left and right leg data. Thus, we averaged both legs data for the sake of simplification.

We found a statistically significant difference in walking velocity from the ANOVA, $F(4,119) = 56.26$, $p < .001$; and effect size, $\eta^2 = 0.08$. In addition, we discovered a statistically significant improvement in step length and stride length ($p < .001$). Then, we performed post hoc two-tailed paired t-tests for within-group comparisons and two-tailed independent sample t-tests for between-group comparisons in order to identify differences between specific study conditions.

6.1 Participants With MI: Within-Group Comparisons

6.1.1 Non-VR Baseline vs. VR Baseline. Walking velocity was significantly lower in the VR baseline without the visual feedback condition (mean, $M = 115.74$, standard deviation, $SD = 3.22$) compared to the non-VR baseline without the visual feedback condition ($M = 125.75$, $SD = 3.89$); $t(24) = 9.64$, $p < .001$; and effect size, Cohen's $d = 0.33$. We also found a significant reduction in step length and stride length ($p < .001$).

6.1.2 Spatial Visual vs. VR Baseline. There was no significant difference in walking velocity in the spatial visual feedback condition ($M = 116.83$, $SD = 3.88$) compared to VR baseline without visual feedback condition; $t(24) = 1.87$, $p = .07$, $d = 0.14$. There was no substantial difference for other gait metrics.

6.1.3 Static visual vs. VR Baseline. Our results indicated that walking velocity was significantly increased in static visual than in VR baseline without visual feedback; $t(24) = 10.2$, $p < .001$, $d = 0.71$. We noticed a substantial difference ($p < .001$) in step length and stride length in static condition than VR baseline without visual feedback.

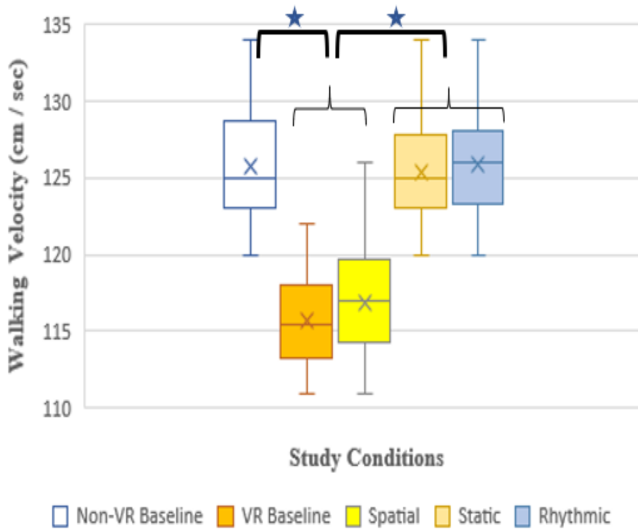

Figure 4: Walking velocity for all participants with MI

Thus, static visual feedback outperformed the VR baseline without visual feedback.

6.1.4 Rhythmic visual vs. VR Baseline. We obtained a significant increase in walking velocity in rhythmic than VR baseline without visual feedback; $t(24) = 10.39$, $p < .001$, $d = 0.75$. For step length and stride length, there was also a significant increase ($p < .001$).

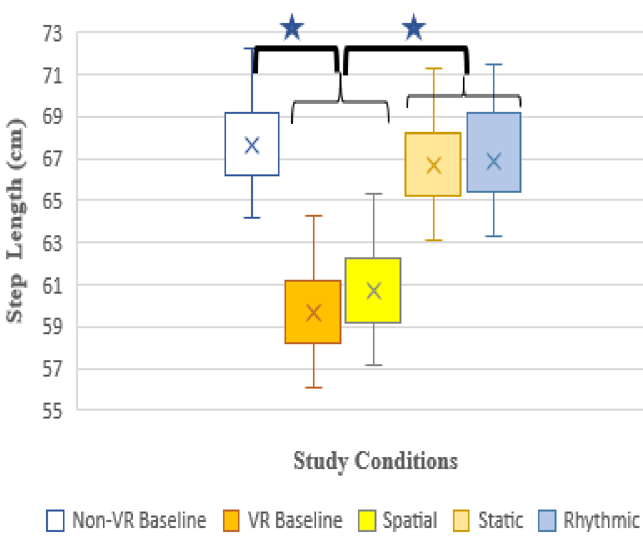

Figure 5: Step length for all participants with MI

6.1.5 Spatial visual vs. Static visual. Experimental results revealed that walking velocity decreased in thespatial visual feedback condition relative to static visual feedback condition; $t(24) = 8.1$, $p < .001$, $d = 0.5$. We discovered a statistically significant decrease ($p < .001$) in step length and stride length for spatial visual feedback condition than static visual feedback condition.

6.1.6 Spatial visual vs. Rhythmic visual. We noticed a significant decrease in walking velocity in spatial than rhythmic visual feedback ($M = 125.88$, $SD = 3.44$); $t(24) = 8.24$, $p < .001$, $d = 0.5$. Also, step length and stride length for spatial visual feedback decreased significantly ($p < .001$) than the rhythmic visual feedback. The findings showed that rhythmic visual feedback might be more beneficial for gait performance than spatial visual feedback.

6.1.7 Static visual vs. Rhythmic visual. We did not find a significant difference in walking velocity between static and rhythmic visual feedback; $t(24) = 1.86$, $p = .08$, $d = 0.14$. We also noticed no significant difference in other gait parameters between static and rhythmic visual feedback conditions. Therefore, the study was equivocal as to whether rhythmic or static visual input is more efficient for improving gait performance.

Fig. 4, 5, and 6 depict the comparisons across five distinct study conditions for walking velocity, step length, and stride length, respectively.

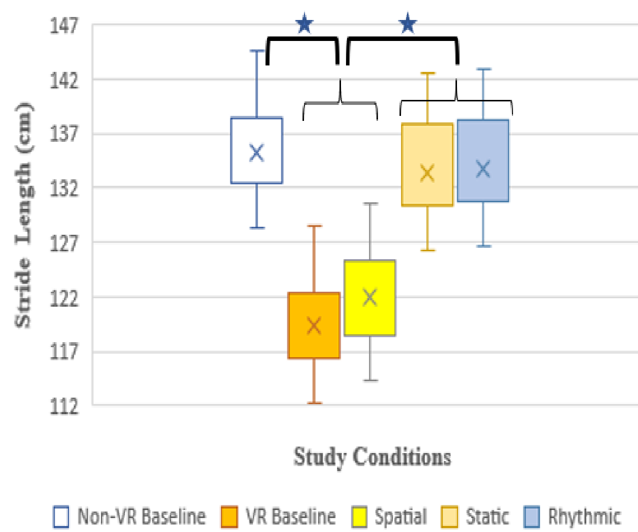

Figure 6: Stride length comparison between study conditions for participants with MI

6.2 Participants Without MI: Within-Group Comparisons

Walking velocity was significantly lower in the VR baseline without the visual feedback condition ($M= 126.375$, $SD = 3.1$) compared to the non-VR baseline without visual feedback condition ($M= 136.33$, $SD = 3.5$); $t(24) = 12.35$, $p < .001$; and effect size, Cohen's $d = 0.33$. There was a significant decrease ($p < .001$) in step length and stride length for the VR baseline without visual feedback condition. These findings suggested that participants without MI experienced gait disturbances in VR environments. However, there was no significant improvement for any gait metrics with any of the VR-based visual feedback conditions (spatial, static, and rhythmic) for participants without MI.

6.3 Between Group Comparisons: Participants with MI vs. Participants Without MI

We conducted independent sample t-tests to find any significant difference between the MI and without MI groups. We found a significant difference in walking velocity ($p < .001$) between individuals with and without MI. However, there was no significant difference in other gait metrics between MI and without MI groups.

6.3.1 Non-VR Baseline Condition: MI vs. Without MI. Experiment results revealed a significant difference between non-VR baseline conditions for participants with MI (M = 125.75, SD = 3.89) and participants without MI (M= 136.33, SD = 3.5); $t(49) = 9.91$, $p < .001$. The results indicated that participants without MI had significantly greater walking velocity than participants with MI in the real-world environment without any visual feedback.

6.3.2 VR Baseline Condition: MI vs. Without MI. We obtained a significant difference between VR baseline conditions for participants with MI (M = 115.74, SD = 3.22) and participants without MI (M= 126.375, SD = 3.1); $t(49) = 11.64$, $p < .001$. For both participant groups, walking velocity was significantly decreased in VR baseline conditions where there was no additional visual feedback. However, participants without MI had greater walking velocity than those with MI.

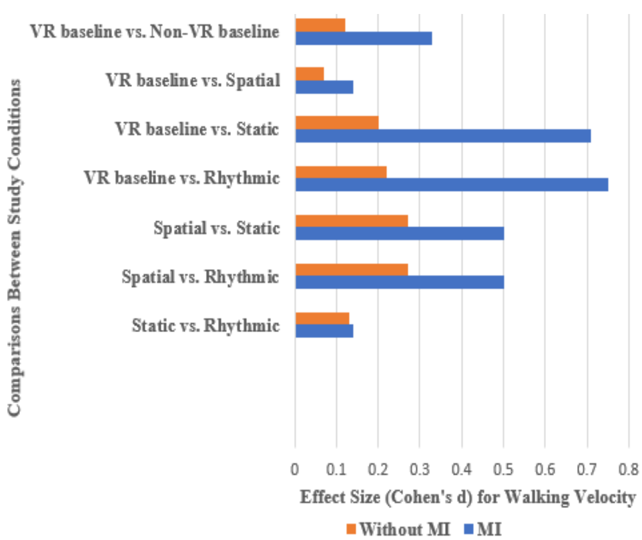

Figure 7: A comparison of effect size between study conditions for participants with and without MI

6.3.3 Spatial Visual Condition: MI vs. Without MI. Our experiment results revealed a significant difference between spatial conditions for participants with MI (M = 118.83, SD = 3.88) and participants without MI (M= 127.83, SD = 3.75); $t(49) = 9.24$, $p < .001$. Similar to the VR baseline condition, walking velocity decreased significantly for both groups and without MI group had greater walking velocity than the MI group. Thus, the results indicated that spatial visual feedback conditions had no significant effect on any participant group.

6.3.4 Static Visual Condition: MI vs. Without MI. We observed a significant difference between static conditions for participants with MI (M = 125.38, SD = 3.39) and participants without MI (M = 129.01, SD = 3.39); $t(49) = 10.23$, $p < .001$. Therefore, static visual feedback conditions improved walking velocity for participants with MI significantly. However, it had no significant effect on participants without MI.

6.3.5 Rhythmic Visual Condition: MI vs. Without MI. Our experiment results revealed a significant difference between rhythmic conditions for participants with MI (M = 125.88, SD = 3.44) and participants without MI (M= 129.61, SD = 3.44); $t(49) = 10.06$, $p < .001$. Similar to the static condition, walking velocity for participants with MI using rhythmic visual feedback improved significantly, whereas it had no significant effect on participants without MI.

Fig. 7 shows the effect size comparisons for participants with and without MI.

6.4 ABC Scale Results

Results revealed a significant difference between participants with MI (M = 69.88, SD = 19.36) and those without MI (M = 94.18, SD = 9.42), $t(24) = 2.09$, $p < .001$. Participants with MI scored 69.88%, indicating the MI participants were with a medium level of physical functioning. However, without MI participants scored 94.18%, confirming their high level of physical functioning.

6.5 SSQ Results

We did not notice a substantial difference in SSQ scores for both groups. While comparing the pre-study and post-study SSQ scores, we obtained $t(24) = 1.46$, $p = .09$, $d = 0.14$ for participants with MI, and $t(24) = 1.17$, $p = .04$, $d = 0.11$ for participants without MI.

7 DISCUSSION

7.1 Gait Disturbances in VR Without Visual Feedback

Mixed ANOVA and posthoc t-tests for both participant groups revealed that step length, stride length, and walking velocity reduced substantially ($p < .001$) in the VR baseline without visual condition compared to the non-VR baseline without visual condition. Thus, gait performance decreased without additional visual feedback, which supported our hypothesis **H1**. Previous research has shown that VR may produce imbalance, leading to gait disturbances for participants [16, 35, 42].

7.2 Gait Improvement in VR-based Visual Feedback Conditions

For participants with MI, results revealed that static and rhythmic VR-based visual conditions increased walking velocity, step length, and stride length significantly ($p < .001$) compared to VR baseline condition. However, spatial visual feedback conditions had no significant effect. We hypothesized that because the spatial visual feedback was fixed in the same position, it did not provide enough visual feedback. However, for static and rhythmic visual feedback conditions, the virtual texture moved with the participants' view, which might have been very helpful for the participants to receive visual feedback. Thus, our hypothesis **H2** was partially supported.

In addition, the effect size comparisons (Fig. 7) clearly showed that static and rhythmic visual feedback had a medium effect (Cohen's d > 0.5) on participants with MI. For the walking tasks, we instructed participants to stay in the middle of the GAITRite and keep walking. The texture was set on both sides of GAITRite, aligned with the middle line of GAITRite. When participants moved a bit from the middle line of the GAITRite to their left or right, the texture also moved in the corresponding direction for static and rhythmic conditions. Thus, the texture helped participants keep walking straight. When participants walked straight, they had better stride length, step length, and step time, which contributed to improved walking velocity. That might be another reason that the texture was helpful for improving walking performance. However, participants without MI experienced a small effect with the VR-based visual feedback conditions, and hence there was no significant improvement. Prior research reported that participants with MI more heavily rely on visual cues than the participants without MI [4, 33] which might be a reason that the visual cues were very effective for the MI group.

Static and rhythmic visual methods were substantially ($p < .001$) better compared to spatial visual feedback conditions, which supported our hypothesis **H3**. Additionally, In prior research, static visual feedback was shown to be useful in the virtual world for improving balance [40]. However, they did not investigate any effect on gait disturbances. Prior studies reported that better postural control contributed to better gait performance [8, 49]. The texture used in [40] provided better postural control for participants with multiple sclerosis (MS), which might be one of the reasons that it provided better gait performance in our study. Also, earlier studies only examined only a specific form of visual feedback, while this research compared four distinct types of visual feedback in immersive VR.

7.3 Gait Differences Between Two Groups

All research conditions revealed significant variations in step length, stride length, and walking velocity between the two groups. There was no significant change in other gait metrics which aligned with our hypothesis **H4** walking velocity, step length, and stride length were affected differently for both groups. However, other gait metrics were affected similarly for both groups of participants. The findings match with prior research [15] by Guo et al where they investigated the influence of full-body avatars with canes on gait. Thus, they did not investigate the effect of any kind of visual feedback.

7.4 Cybersickness

No significant difference was found in SSQ scores for both groups, indicating that participants were not impacted by cybersickness. Participants might have been affected by mild cybersickness because our study consisted of five conditions for the walking task, and three trials for each condition, which took around one and a half hours to complete. When engaging in VR activities for more than 10 minutes, cybersickness is prevalent [6, 23]. As there was no illusory self-motion, our environment was meant to be simple and cybersickness-free [31]. Therefore, we reasoned that cybersickness had no significant impact on the gait data.

7.5 Practical Implications of the Findings

As virtual reality technology develops, it provides creative solutions for improving gait therapy and treating a range of locomotor problems. Additionally, VR-based gait therapies provide customized and flexible training schedules that may be adjusted in accordance with each patient's unique demands and development, producing more successful and efficient rehabilitation outcomes. Furthermore, the incorporation of biofeedback devices in VR can deliver real-time data on gait metrics, allowing patients and therapists to track progress and make required modifications during the training process. The findings can thus be applied to enhance the overall quality of life for those who have gait abnormalities. If the user tasks were changed in our study, such as participants moving laterally, we would have got similar results. In any scenario, the visual feedback should be visible enough to the participants.

7.6 Limitations

In our study, all participants used harnesses for the whole study which might have affected gait performance. Thus, studies with no harness might find different results.

We designed the rhythmic condition at one-second intervals. However, conditions for different time periods (e.g., two seconds) were not examined. Therefore, studies that provide "rhythmic" visual input in different intervals may find different results. We chose a 1-second interval for rhythmic conditions because it was effective in previous research on auditory feedback for balance improvement [25].

During the VR intervention, we assessed gait performance. We did not assess post-study gait effects.

We recreated our exact real lab in VR to compare the gait performance in the real lab with the performance in the same environment but in VR. Additionally, we could add a few other types of VR environments. However, that would make the study potentially longer, and our participants with MS who had less physical ability might not be able to complete the study.

We did not measure if the presented method has an effect on the participants' immersion in the VR environment.

8 CONCLUSION AND FUTURE WORK

This study used head-mounted displays to test the impact of several visual input modalities (spatial, static, and rhythmic) on gait in immersive VR. In our research, static and rhythmic conditions significantly improved walking performance in immersive VR. Static and rhythmic visual feedback outperformed spatial condition significantly. There was no statistically significant difference between static and rhythmic visual feedback. As a consequence of these findings, researchers will be better able to comprehend the various types of visual input for improving walking in an HMD-based VE. Furthermore, the results of this study may help designers create VR experiences that are more usable and accessible for those with mobility problems. In the future, we will investigate multimodal feedback to make real walking in VR more accessible.

ACKNOWLEDGMENTS

The National Science Foundation (IIS 2007041) provided funding for this project. We also thank the people who took part in our study.

REFERENCES

[1] [n. d.]. [GaitRite Manual] Details Gait Parameters for GaitRite Walkway System. https://www.procarebv.nl/wp-content/uploads/2017/01/Technische-aspecten-GAITrite-Walkway-System.pdf. Accessed: 2021-08-30.

[2] Renan Adachi, Emily M Cramer, and Hayeon Song. 2022. Using virtual reality for tourism marketing: A mediating role of self-presence. *The Social Science Journal* 59, 4 (2022), 657–670.

[3] Yuri Agrawal, John P Carey, Charles C Della Santina, Michael C Schubert, and Lloyd B Minor. 2009. Disorders of balance and vestibular function in US adults: data from the National Health and Nutrition Examination Survey, 2001-2004. *Archives of internal medicine* 169, 10 (2009), 938–944.

[4] Octavia Calder-Dawe, Karen Witten, and Penelope Carroll. 2020. Being the body in question: Young people's accounts of everyday ableism, visibility and disability. *Disability & Society* 35, 1 (2020), 132–155.

[5] Andrea Canessa, Paolo Casu, Fabio Solari, and Manuela Chessa. 2019. Comparing Real Walking in Immersive Virtual Reality and in Physical World using Gait Analysis.. In *VISIGRAPP (2: HUCAPP)*. 121–128.

[6] Eunhee Chang, Hyun Taek Kim, and Byounghyun Yoo. 2020. Virtual reality sickness: a review of causes and measurements. *International Journal of Human–Computer Interaction* 36, 17 (2020), 1658–1682.

[7] Tara Cornwell, Jane Woodward, Mengnan Wu, Brennan Jackson, Pamela Souza, Jonathan Siegel, Sumitrajit Dhar, Keith E Gordon, et al. 2020. Walking with ears: altered auditory feedback impacts gait step length in older adults. *Frontiers in Sports and Active Living* 2 (2020), 38.

[8] Ayoob Davoodi, Omid Mohseni, Andre Seyfarth, and Maziar A Sharbafi. 2019. From template to anchors: transfer of virtual pendulum posture control balance template to adaptive neuromuscular gait model increases walking stability. *Royal Society open science* 6, 3 (2019), 181911.

[9] Paula Epure, Cristina Gheorghe, Thomas Nissen, Laurentiu-Octavian Toader, Alexandru Nicolae, Steven SM Nielsen, Daniel Juul Rosengreen Christensen, Anthony Lewis Brooks, and Eva Petersson. 2014. Effect of the Oculus Rift head mounted display on postural stability. In *The 10th International Conference on Disability Virtual Reality & Associated Technologies: Proceedings*. Reading University Press, 119–127.

[10] Sharif Mohammad Shahnewaz Ferdous, Imtiaz Muhammad Arafat, and John Quarles. 2016. Visual feedback to improve the accessibility of head-mounted displays for persons with balance impairments. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 121–128.

[11] Sharif Mohammad Shahnewaz Ferdous, Tanvir Irfan Chowdhury, Imtiaz Muhammad Arafat, and John Quarles. 2018. Investigating the reason for increased postural instability in virtual reality for persons with balance impairments. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. 1–7.

[12] Lennie Gandemer, Gaetan Parseihian, Richard Kronland-Martinet, and Christophe Bourdin. 2017. Spatial cues provided by sound improve postural stabilization: evidence of a spatial auditory map? *Frontiers in neuroscience* 11 (2017), 357.

[13] Shashank Ghai, Ishan Ghai, and Alfred O Effenberg. 2018. Effect of rhythmic auditory cueing on aging gait: a systematic review and meta-analysis. *Aging and disease* 9, 5 (2018), 901.

[14] Rongkai Guo, Gayani Samaraweera, and John Quarles. 2013. The effects of VEs on mobility impaired users: Presence, gait, and physiological response. In *Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology*. 59–68.

[15] Rongkai Guo, Gayani Samaraweera, and John Quarles. 2015. Mobility impaired users respond differently than healthy users in virtual environments. *Computer Animation and Virtual Worlds* 26, 5 (2015), 509–526.

[16] John H Hollman, Robert H Brey, Tami J Bang, and Kenton R Kaufman. 2007. Does walking in a virtual environment induce unstable gait?: An examination of vertical ground reaction forces. *Gait & posture* 26, 2 (2007), 289–294.

[17] Corinne GC Horlings, Mark G Carpenter, Ursula M Küng, Flurin Honegger, Brenda Wiederhold, and John HJ Allum. 2009. Influence of virtual reality on postural stability during movements of quiet stance. *Neuroscience letters* 451, 3 (2009), 227–231.

[18] Brian Horsak, Mark Simonlehner, Lucas Schöffer, Bernhard Dumphart, Arian Jalaeefar, and Matthias Husinsky. 2021. Overground Walking in a Fully Immersive Virtual Reality: A Comprehensive Study on the Effects on Full-Body Walking Biomechanics. *Frontiers in bioengineering and biotechnology* 9 (2021).

[19] Klaus Jahn, Andreas Zwergal, and Roman Schniepp. 2010. Gait disturbances in old age: classification, diagnosis, and treatment from a neurological perspective. *Deutsches Ärzteblatt International* 107, 17 (2010), 306.

[20] Omar Janeh and Frank Steinicke. 2021. A Review of the Potential of Virtual Walking Techniques for Gait Rehabilitation. *Frontiers in Human Neuroscience* 15 (2021).

[21] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology* 3, 3 (1993), 203–220.

[22] Jakob Ketterer, Steffen Ringhof, Dominic Gehring, and Albert Gollhofer. 2022. Sinusoidal optic flow perturbations reduce transient but not continuous postural stability: A virtual reality-based study. *Frontiers in physiology* (2022), 988.

[23] Hyewon Kim, Dong Jun Kim, Won Ho Chung, Kyung-Ah Park, James DK Kim, Dowan Kim, Kiwon Kim, and Hong Jin Jeon. 2021. Clinical predictors of cybersickness in virtual reality (VR) among highly stressed people. *Scientific reports* 11, 1 (2021), 1–11.

[24] Alison Lott, Etienne Bisson, Yves Lajoie, Joan McComas, and Heidi Sveistrup. 2003. The effect of two types of virtual reality on voluntary center of pressure displacement. *Cyberpsychology & behavior* 6, 5 (2003), 477–485.

[25] M Rasel Mahmud, Michael Stewart, Alberto Cordova, and John Quarles. 2022. Auditory Feedback for Standing Balance Improvement in Virtual Reality. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 782–791.

[26] M Rasel Mahmud, Michael Stewart, Alberto Cordova, and John Quarles. 2022. Standing Balance Improvement Using Vibrotactile Feedback in Virtual Reality. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*. 1–11.

[27] M Rasel Mahmud, Michael Stewart, Alberto Cordova, and John Quarles. 2022. Vibrotactile Feedback to Make Real Walking in Virtual Reality More Accessible. *arXiv preprint arXiv:2208.02403* (2022).

[28] Dario Martelli, Boxi Xia, Antonio Prado, and Sunil K Agrawal. 2019. Gait adaptations during overground walking and multidirectional oscillations of the visual field in a virtual reality headset. *Gait & posture* 67 (2019), 251–256.

[29] Armando Martinez, Antonio Iyda Paganelli, and Alberto Raposo. 2018. Analysing balance loss in vr interaction with hmds. *Journal on Interactive Systems* 9, 2 (2018).

[30] Sergo Martirosov, Marek Bureš, and Tomáš Zítka. 2022. Cyber sickness in low-immersive, semi-immersive, and fully immersive virtual reality. *Virtual Reality* 26, 1 (2022), 15–32.

[31] Michael E McCauley and Thomas J Sharkey. 1992. Cybersickness: Perception of self-motion in virtual environments. *Presence: Teleoperators & Virtual Environments* 1, 3 (1992), 311–318.

[32] Atsuo Murata. 2004. Effects of duration of immersion in a virtual reality environment on postural stability. *International Journal of Human-Computer Interaction* 17, 4 (2004), 463–477.

[33] Rosa Ortiz-Gutiérrez, Roberto Cano-de-la Cuerda, Fernando Galán-del Río, Isabel María Alguacil-Diego, Domingo Palacios-Ceña, and Juan Carlos Miangolarra-Page. 2013. A telerehabilitation program improves postural control in multiple sclerosis patients: a Spanish preliminary study. *International journal of environmental research and public health* 10, 11 (2013), 5697–5710.

[34] Lynda Elaine Powell and Anita M Myers. 1995. The activities-specific balance confidence (ABC) scale. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 50, 1 (1995), M28–M34.

[35] Lara I Riem, Brian D Schmit, and Scott A Beardsley. 2020. The Effect of Discrete Visual Perturbations on Balance Control during Gait. In *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE, 3162–3165.

[36] Maxime T Robert, Laurent Ballaz, and Martin Lemay. 2016. The effect of viewing a virtual environment through a head-mounted display on balance. *Gait & posture* 48 (2016), 261–266.

[37] JM Ross, OJ Will, Z McGann, and R Balasubramaniam. 2016. Auditory white noise reduces age-related fluctuations in balance. *Neuroscience letters* 630 (2016), 216–221.

[38] Gayani Samaraweera, Rongkai Guo, and John Quarles. 2013. Latency and avatars in virtual environments and the effects on gait for persons with mobility impairments. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 23–30.

[39] Gayani Samaraweera, Alex Perdomo, and John Quarles. 2015. Applying latency to half of a self-avatar's body to change real walking patterns. In *2015 IEEE Virtual Reality (VR)*. IEEE, 89–96.

[40] Sharif Mohammad Shahnewaz Ferdous, Tanvir Irfan Chowdhury, Imtiaz Muhammad Arafat, and John Quarles. 2021. Static Rest Frame to Improve Postural Stability in Virtual and Augmented Reality. *Frontiers in Virtual Reality* 1 (2021), 582169.

[41] Pooya Soltani and Renato Andrade. 2020. The influence of virtual reality head-mounted displays on balance outcomes and training paradigms: A systematic review. *Frontiers in sports and active living* 2 (2020), 233.

[42] Björn Sondell, Lars Nyberg, Staffan Eriksson, Björn Engström, Anders Backman, Kenneth Holmlund, Gösta Bucht, and Lillemor Lundin-Olsson. 2005. Altered walking pattern in a virtual environment. *Presence* 14, 2 (2005), 191–197.

[43] Teresa M Steffen, Timothy A Hacker, and Louise Mollinger. 2002. Age-and gender-related test performance in community-dwelling elderly people: Six-Minute Walk

Test, Berg Balance Scale, Timed Up & Go Test, and gait speeds. *Physical therapy* 82, 2 (2002), 128–137.

[44] Madelyn N Stevens, Dennis L Barbour, Meredith P Gronski, and Timothy E Hullar. 2016. Auditory contributions to maintaining balance. *Journal of Vestibular Research* 26, 5-6 (2016), 433–438.

[45] Hiroki Tanaka, Manabu Nankaku, Toru Nishikawa, Takuya Hosoe, Honami Yonezawa, Hiroki Mori, Takayuki Kikuchi, Hidehisa Nishi, Yasushi Takagi, Susumu Miyamoto, et al. 2019. Spatiotemporal gait characteristic changes with gait training using the hybrid assistive limb for chronic stroke patients. *Gait & posture* 71 (2019), 205–210.

[46] Martha L Walker, Stacie I Ringleb, George C Maihafer, Robert Walker, Jessica R Crouch, Bonnie Van Lunen, and Steven Morrison. 2010. Virtual reality–enhanced partial body weight–supported treadmill training poststroke: feasibility and effectiveness in 6 subjects. *Archives of physical medicine and rehabilitation* 91, 1 (2010), 115–122.

[47] Anika Weber, Julian Werth, Gaspar Epro, Daniel Friemert, Ulrich Hartmann, Yiannis Lambrianides, John Seeley, Peter Nickel, and Kiros Karamanidis. 2022. Head-mounted and hand-held displays diminish the effectiveness of fall-resisting skills. *Sensors* 22, 1 (2022), 344.

[48] Carla Winter, Florian Kern, Dominik Gall, Marc Erich Latoschik, Paul Pauli, and Ivo Käthner. 2021. Immersive virtual reality during gait rehabilitation increases walking speed and motivation: a usability evaluation with healthy participants and patients with multiple sclerosis and stroke. *Journal of neuroengineering and rehabilitation* 18, 1 (2021), 1–14.

[49] Galit Yogev-Seligmann, Nir Giladi, Leor Gruendlinger, and Jeffrey M Hausdorff. 2013. The contribution of postural control and bilateral coordination to the impact of dual tasking on gait. *Experimental brain research* 226 (2013), 81–93.