Investigating Walking Performance and Experience with Different Locomotion Technologies in VR

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Figure 1: The user study for investigating users' walking performance and experience with various walking methods in different levels of fidelity VR. (a) shows the high-fidelity virtual scenario with a triangle walking trajectory, (b) shows a low-fidelity virtual scenario with a rectangle walking trajectory, (c) shows the participant walking with the Real Walking method, (d) shows the participant walking on the omnidirectional treadmill, (e) shows the participant walking with controller method.

Abstract

Locomotion is crucial for moving in virtual worlds, and a plausible but realistic implementation is an essential component of locomotion technologies. Various locomotion technologies, such as treadmills or controller locomotion approaches have been developed to simulate continuous walking behavior in VR. However, it is unknown which locomotion technique provides higher walking performance and better walking experience. Hence, we conducted a user study with 15 participants to systematically compare three walking methods (real walking, walking with VR device controllers, and walking on an omnidirectional treadmill) in VR. We found that the omnidirectional treadmill decreased walking performance and increased simulator sickness, negatively affecting locomotion compared to real walking and using VR controllers. Furthermore, visual fidelity also affects walking performance in VR. We discuss potential factors for the negative performance of the omnidirectional treadmill in virtual walking. Our work contributes to the important area of locomotion techniques for immersive technologies.

MUM '24, December 01–04, 2024, Stockholm, Sweden

ACM ISBN 979-8-4007-1283-8/24/12
https://doi.org/10.1145/3701571.3701603

CCS Concepts

• **Human-centered computing → Empirical studies in HCI**; **Virtual reality**.

Keywords

Virtual Reality, Locomotion Technology, Walking Performance, Fidelity, Simulator Sickness

ACM Reference Format:
Yu Wang, Jakob Eckkrammer, Martin Kocur, and Philipp Wintersberger. 2024. Investigating Walking Performance and Experience with Different Locomotion Technologies in VR. In *International Conference on Mobile and Ubiquitous Multimedia (MUM '24), December 01–04, 2024, Stockholm, Sweden.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3701571.3701603

1 Introduction

Virtual Reality (VR) simulates perceptual and sensorimotor virtual environments (VEs), enabling interaction between users and the VEs as they would in reality. Locomotion is a popular research topic in VR, which enables movement from one place to another [7]. Meanwhile, walking methods are essential components of locomotion technologies. The research of walking in immersive virtual environments (IVEs) is divided into two dimensions: the development of wide-area trackers so users can really walk around [76], and the development of body-active surrogates for a natural walking simulation [72]. Natural walking with synchronized speed, direction, and distance perception in IVEs has become an important technological component for providing highly immersive walking sensations in VR [37]. Nilsson et al. [55] have systematically categorized the existing VR natural walking techniques into proxy gestures, repositioning systems, and redirection techniques. Locomotion based on proxy gestures performs gestures of the lower body or upper body serving as a proxy for actual steps [55, 65]. Walk-in-Place (WIP) and arm-swing are two cost-effective approaches to walking with proxy gestures [78], with WIP the footsteps in place are registered via a physical interface detecting discrete gait events [9, 10], and arm-swing interface refers to translating users forward in VE through the detection of the motion of their arm swing [48]. On the other hand, Boletsis et al. [8] also created a taxonomy for existing locomotion technologies and categorized them into motion-based, room-scale-based, and controller-based locomotion technologies. For motion-based locomotion, the physical movements are utilized to enable the interaction while supporting continuous motion in open VR spaces; room-scale locomotion relies on the tracking system of the VR devices and is limited by the real environment's size; and finally, controller-based locomotion directs the continuous movement in VR via a gamepad or controller [6]. Treadmills are the commonly used repositioning systems for natural walking in VR, which implements walking by eliminating the user's forward movement in the physical environment through elaborate mechanical systems [55]. The omnidirectional treadmill (ODT) can support free walking in any direction in IVEs [19, 30] and accommodates different gait velocities during overground locomotion [31]. The combination of head-mounted display (HMD) and treadmill walking is expected to realize a fully immersive VR [44, 62].

Various locomotion technologies show different performances and influences on users' walking experience and performance in VR [75]. Existing research showed that using physical bipedal moving methods would obtain significantly better spatial orientation than haptic devices [13]. Whitton et al. [77] compared real walking, WIP, and controller flying and found that physically walking to explore a VE was better than both WIP and controller locomotion. However, real walking with large tracking systems is expensive and limits exploration due to the size of the tracking areas in physical space. Stepping in place appears to be the most common lower-body gesture, alternatives have been proposed to translate moving in VR as well. The study from Nilsson et al. [54] also indicated upper-body gestures equally as natural as WIP locomotion and less fatiguing. It is already known that the conflicting sensory of the visual system and vestibular will induce simulator sickness [60, 70] and affect the movement in VEs. In addition, the disorientation caused by less corresponding bodily movement is another disadvantage of virtual walking [18, 20]. Different methods to facilitate natural walking behavior could affect users' perceptions [1]. Fidelity is one of the core concepts in VR research. It is defined as a measure of the realism level of the VE and its resultant ability to convince the feelings of presence [51]. Previous research also indicated that key elements of psychological, affective, and ergonomic fidelity, are the real determinants of VR system fidelity [25]. A room-scale VR configuration allows the physical movement of the user within an interactive area while reflecting their real-world motion in the VE, and it develops more realistic applications that are highly interactive and engaging [66].

However, the effect of different walking approaches on actual walking experience and performance in VR has not been examined, as well as how much the fidelity of the virtual scenario could incur the changing of users' virtual walking performance in VEs. Therefore, we conducted a study to implement multiple walking methods (real walking, controller walking, and an omnidirectional treadmill) and calculated the deviated area between the ideal and the actual walking path to evaluate the influence of different walking methods on dynamic position maintenance in VR. We found that the ODT induced lower maintenance of dynamic position during virtual walking. We also showed that a high-fidelity VE increased the ability of dynamic position maintenance during walking in VR. We discuss possible factors for the negative performance of the ODT in natural walking in VR. Our work extends the research of locomotion in VR by comparing users' walking performance and experience with various methods in both low- and high-fidelity VR.

2 Related Work

Locomotion in VR is integrated with vestibular, proprioceptive, and visual sensory inputs. Especially the visual inputs provide users with essential cues for orientation and self-movement perception during moving [61]. Postural stability, also known as postural equilibrium [17], indicates the capability of an individual to maintain the body position and balance in the space for movements [56, 79]. The research by Hollman et al. [26] revealed that VR can induce postural instability in standing and walking, as quantified with kinematic gait parameters, which are typically utilized to evaluate gait instability. Meanwhile, the decreased step velocity and length [50], the increased gait width [38], the increased variability in stride velocity [46] and width [3], and the increased mediolateral displacement of the individual mass center [15] are all considered as the signs of gait instability. The research from Simoneau et al. [67] indicated that postural instability is caused by using visual perturbations. Blanks et al. [4] used a force plate to measure the resultant variation in postural stability to evaluate the effect of the visual system on balance. To explore the visual polarity and scene rotation in spatial VE, Richards et al. [61] conducted a study to quantify the influence of visual scene variables on postural stability through locomotion with a treadmill. Since the degeneration of the balance control system in the elderly, the measure of equilibrium conditions is frequently required in many pathologies, Placidi et al. [59] proposed a low-cost real-time virtual system for postural stability assessment at home. Existing research also showed that postural sway in standing increases in VR environments [27], and VR aggravates visual-vestibular conflicts [16, 17]. Besides, Dietz et al. [22] also investigated the stress response that affects the dynamic balance of human upright gait in their study. Some research also worked on the exploration of the correlation between visual input and postural stability in VR [40]. Previous work demonstrated that the manipulation of the amount or type of visual stimulus has been used for assessments or training of postural balance [73]. Dynamic visual images or minimal visual stimuli could also induce a decrease in the postural stability [57]. Menzies et al. [51] proposed that postural stability can be used as an objective behavioral measure of visual fidelity.

In addition to studying the postural stability affected by VR, researchers also use VR as a tool for balance training [32], or gait rehabilitation [11, 71], to improve walking safety and balance control [74]. Rehabilitation in VR enables interventions by manipulating training duration or intensity, meanwhile, the multi-sensory feedback can also satisfy clinical demands for intensive and repetitive patient training [21, 35], for instance, providing a therapeutic platform with potential movement for patients with neurological conditions [5], such as stroke [29, 36] and other nervous system diseases [42, 53]. Peñasco-Martín et al. [58] and Gallagher et al. [24] also revealed in the previous studies that training with VR enhances users' interest in the rehabilitation process. Thus, the implementation of virtual walking technologies offers promising potential even in therapeutic rehabilitation.

3 Apparatus: Walking Implementation in Virtual Reality

We investigate dynamic position maintenance with different natural walking technologies in high- and low-fidelity virtual scenarios through walking tasks in VR. For the first objective, we intended to compare the dynamic position maintenance when impacted by different walking methods. As a second objective, we also evaluated the influence of fidelity on position maintenance. To get access to the evaluations, we designed the walking tasks: users get a view of reference walking trajectories in VR and walk once with each of the three walking methods: Real Walking, Controller Walking, and ODT. We compared the differences between the actual walking trajectories and the reference walking trajectories to assess the performance of dynamic position maintenance in virtual walking.

Through the immersive VR system, users can experience the interaction and the virtual space, and the phenomenon where users act and feel also indicates users' presence in this VR system [68]. The study from Lee et al. [39] revealed that walking interactions in VR can improve immersion and presence and prevent sickness in VR applications. However, the walking interactions in their study were conducted via a gamepad, hand interface, and a portable simulator for in-place gestures instead of real walking or with the treadmill. Nevertheless, based on the sensory conflict theory [12], the source of sickness users are experiencing might be differing. Walking on an ODT might lead to a different sensory mismatch that could cause motion sickness, since in the case of treadmill walking, users perceive to be visually moving forward as they walk, but they are actually walking on the spot [43]. Therefore, the evaluations of immersion, presence, and simulator sickness of the different natural walking methods in VR are the additional objectives of this study.

3.1 Implementation of Real Walking, Controller Walking, and ODT in VR Walking

The VEs and the walking task in this study are developed in the game engine Unity and implemented with the HMD Oculus Quest 2. During the experiment, participants need to complete the walking tasks in VR with three walking methods: Real Walking, Controller Walking, and ODT. The Real Walking method relies on the accurate position-tracking function of the HMD, participants can freely walk in the physical space, and their movement in reality will be tracked and reflected in VR synchronously. To implement the Real Walking method, we experimented with a room-scale VR, and the physical room space for the walking task is large, approximately $5m * 5m$, which is sufficient to be encompassed by the space tracking capability of the HMD. The advent of room-scale VR has emerged in recent years, where users configure a designated physical area allowing users to naturally navigate and move [41]. With the Controller Walking, participants held the controllers in hand, and the input of the controller directed their movements during the walking task. The motion input from the left controller was transmitted to the VR project to effectuate the virtual movement. For walking on the ODT, We used the KAT Walk C 2 Core in this study, which is set up to work with Unity through the supplied KAT Unity Integration SDK [1].

3.2 Walking Scenarios in VR with Different Fidelity

To explore the impact of visual fidelity on people's walking behavior, we designed two distinct virtual scenarios with low- and high fidelity. In the high-fidelity virtual scenario, we constructed a simulation of a simple room featuring an open central area to facilitate unobstructed walking along the designated trajectories. The room is rectangular, includes orthogonal corners, and is outfitted with windows, doors, and minimalist furniture, thereby offering multiple reference points to assist in navigation. Compared to the high-fidelity scenario, the low-fidelity virtual scenario features a wooden floor on the ground plane within an open space with daylight, which provides minimal visual cues to facilitate locomotion behavior. The walking trajectories remain consistent across both high- and low-fidelity scenarios.

3.3 Walking Trajectories in Experiments Design

In both low- and high-fidelity scenarios, we established two distinct walking trajectories: one triangular and one rectangular, which showed as bright green color paths in the experimental VEs; see Figure 1. Before commencing the walking task, the reference walking trajectories were presented to the participants. Subsequently, participants were required to walk along the memorized paths after

[1] https://www.kat-vr.com/pages/sdk

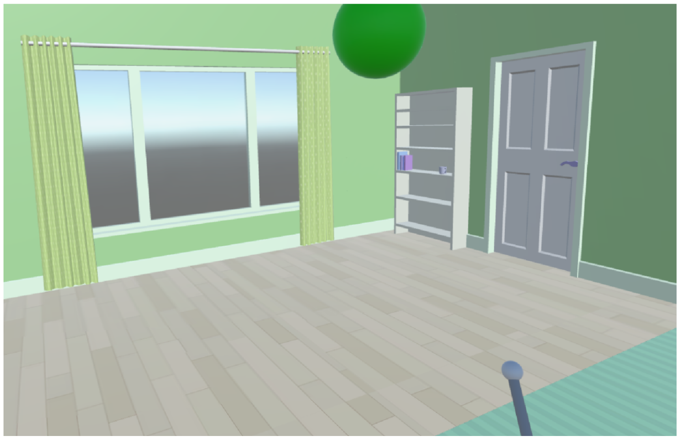


Figure 2: The sphere turned into color green, the walking trajectory vanished, and started to track the position during the walking process.

the guiding trajectories had disappeared. Participants' positions in the VE were recorded in each frame in Unity based on the rate of 50 to 72 frames per second for the HMD Oculus Quest 2, and the positions were recorded when there was movement detected between frames. We used the open-source software library Clipper2 [2], which provides various functions to process different calculations for vector shapes. To evaluate the maintenance of dynamic position in walking, we measured the deviation of the actual walking trajectories and the reference walking trajectories in VR. We calculated the symmetric difference between two vector shapes; one was shaped by the participants' actual walking path, and the other one was the shape of the reference walking trajectories (see section 4.1.1). A small sphere is always visualized in the scenarios, when participants are ready to conduct the walking task, they can trigger the small sphere to disable the presentation of the walking trajectory and start to record their frame-calculated position during the walking process, see Figure 2. The color of the sphere turns from red to green when it is triggered, as soon as the participants accomplished the walking task, they had to trigger the sphere manually again to end the position tacking, and the sphere turned back to the color red.

4 User Study

We conducted a user study in a within-participants design to explore the impact of various natural walking methods and VR fidelity on users' dynamic position maintenance in virtual walking. In the study, we measured two independent variables (IVs); the first independent variables are the **Walking Methods** (Real Walking, Controller Walking, and ODT) used to facilitate the walking behavior in VR. The second independent variable is the **Visual Fidelity** (low and high fidelity) of the VE. The walking behavior employing each of these walking methods was executed within virtual scenarios of both high- and low-fidelity.

[2]https://angusj.com/clipper2/Docs/Overview.htm

4.1 Measures

Based on the consideration of the different technical mechanisms of each natural walking method (Real Walking, Controller Walking, and the ODT), and the significant impact of display fidelity on users' strategy and performance in VR [49]. We proposed the following aspects for the investigation of how different natural walking methods and fidelity affect the dynamic position maintenance and experience of walking in VR. Besides the position maintenance evaluation, we also measured participants' involvement, spatial presence, and realism in VR through the Igroup Presence Questionnaire (IPQ) [64], as well as the users' simulator sickness via the Simulator Sickness Questionnaire (SSQ) [34] for the subjective data analysis to estimate the walking experience in VR.

4.1.1 Objective Measures: Dynamic Position Maintenance Metrics. In our study, we calculate the difference between the areas formed by the actual walking paths of participants and the ideal walking areas formed by the pre-designed reference walking trajectories in VEs to indicate the dynamic position maintenance when participants walk in VR. This measurement was inspired by Mattes [47], who utilized a similar model to quantify drivers' performance in automotive lane change maneuvers. In their study, the area is sensitive to multiple performance parameters, including perception, reaction, maneuvering, and lane keeping. Translated to our problem of assessing participants' walking performance in VR, the area combines how well participants were able to (1) remember the reference trajectory, and (2) balance/walk straight. The participant's position was detected in every frame when they walked in the VEs. The recorded position constructed the actual walking path to compose the actual walking area. Correspondingly, the reference walking trajectories (the triangle and rectangle walking trajectories) specify the ideal walking area. A larger discrepancy between the actual walking area and the ideal walking area indicates lower performance of dynamic position maintenance in walking.

4.1.2 Subjective Measures: Walking Experience in VR. We assessed individual walking experiences with different walking methods in VR using the Igroup Presence Questionnaire (IPQ). The questionnaire measured three key dimensions: Involvement, which measures the participant's engagement within the VEs during walking; Spatial Presence, which evaluates the sensation of physical presence within the VEs; and Experienced Realism, which indicates the subjective perception of realism experienced in the VE during walking. We used Simulator Sickness Questionnaire (SSQ) to measure the levels of simulator sickness of participants to assess how different walking methods in VR influence the incidence of such sickness symptoms. There are existing studies that revealed that high-fidelity can improve human performance in VR [63, 80] and have positive effects on the user experience [49]. Therefore, we only measured the subjective walking experience in VR with high-level fidelity.

4.2 Participants

We recruited 15 participants in the user study, 11 male and 4 female, they are all aged in the range of 20-32 years old ($M = 23.9, SD = 3.3$). None of the participants possessed a condition that could impair their equilibrium or spatial perception in daily activities.

Over half of the participants had less or zero experience with VR technology before. All participants voluntarily consented to join the experiment.

4.3 Procedure

At the beginning of the study, participants got a brief introduction about the topic of the research and completed a short questionnaire to collect demographic data. In this study, participants executed the walking task using three methods (Real Walking, Controller Walking, and ODT) within two VEs with two fidelity levels (high- and low-fidelity), which implies that each participant needs to accomplish six trials of the walking task. In each trial, participants walked with one of the three walking methods in one VE. After the participants finished the walking task in both low- and high-fidelity VEs, they would start a new trial with another walking method. The sequence of the walking methods conditions in the study was quasi-randomized to mitigate order effects. Since the rectangle walking trajectory features right angles at its corners, the difficulty of orientation and navigation is reduced in this walking path. Therefore, a triangular walking trajectory has also been employed to enhance the complexity of the walking task for participants, and in each trial, participants need to accomplish the walking task with both rectangle and triangle trajectories.

To minimize biases, triangular and rectangular walking trajectories were utilized for each participant in the walking task across both high- and low-fidelity virtual scenarios using all three methods. Therefore, in each trial, participants walked following both triangle and rectangle walking trajectories for two rounds consecutively with one walking method in one condition of VR fidelity. Additionally, the sequence of the walking trajectory shape was randomly assigned. Participants were also required to complete the questionnaires after each trial of the walking task in VR, and all participants accomplished the complete experiment within 40 minutes.

5 Results

In this section, we present the quantitative results from objective measurements and subjective questionnaires. We employed repeated-measures ANOVAs and Bonferroni-corrected post-hoc tests to analyze postural stability with different walking methods (Real Walking, Controller Walking, and ODT) in both high- and low-fidelity VR. It was conducted by calculating and comparing the deviation between actual and ideal walking areas (in square meters). Additionally, we assessed the VR experience using the IPQ and SSQ questionnaires. The descriptive statistics are summarized in the accompanying Table 1.

5.1 Dynamic Position Maintenance in Virtual Walking with Various Methods in VR with Different Fidelity

When comparing the effectiveness of walking methods (Real Walking, Controller Walking, and ODT) on dynamic position maintenance by evaluating the difference between actual and ideal walking areas, it was found that various walking methods significantly impact participants' performance of dynamic position maintenance ($F = 7.562$, $p = .002$, $\eta^2 = .143$) in VR (see Figure 3a). Post hoc comparisons revealed that compared to the Real Walking method, walking with the ODT ($Md = 3.375, p = .002$) significantly decreases the maintenance of the dynamic position during walking. On the other hand, the result also indicated a significant effect of different levels of fidelity ($F = 33.070$, $p < .001$, $\eta^2 = .248$) on the performance of position maintenance when participants walk in VR (see Figure 3a). The low-fidelity virtual scenario ($Md = 3.682, p < .001$) significantly decreases position maintenance performance during walking in VR. Additionally, the interaction effects of walking methods and fidelity also show a significant impact on the dynamic position maintenance ($F = 5.063$, $p = .013$, $\eta^2 = .064$) (see Figure 3c). The combination of walking methods ODT with walking in a low-fidelity virtual scenario reduces position maintenance performance compared to walking with an ODT in high-fidelity VR ($Md = 5.861, p < .001$), Real Walking in both high-fidelity ($Md = 6.960, p < .001$) and low-fidelity ($Md = 5.652, p < .001$), and Controller Walking in VR with high-fidelity ($Md = 7.069, p < .001$). Moreover, walking with the controller in low-fidelity VR also significantly induces lower performance of dynamic position maintenance compared to walking with the controller in high-fidelity VR ($Md = 3.877, p = .009$) and Real Walking in high-fidelity VR ($Md = 3.767, p = .032$).

5.2 Experience of Walking in VR

Based on the collected IPQ ratings, we were unable to prove a significant difference between the three walking methods affected Involvement ($F = .171$, $p = .843$, $\eta^2 = .012$). Nevertheless, the findings also revealed significant differences in Realism ($F = 6.640$, $p = .004$, $\eta^2 = .322$, see Figure 4a) and Spatial Presence ($F = 4.872$, $p = .015$, $\eta^2 = .258$, see Figure 4b), when participants walked with different methods in VR. The results from Post hoc comparisons revealed that the Real Walking method can significantly increase both the Realism ($Md = -1.250, p = .003$) and Spatial Presence ($Md = -.533, p = .013$) when walking in VR compared to the method Controller Walking simultaneously. The results of SSQ measures also revealed a significant difference between the three methods impacted on the simulator sickness ($F = 7.235$, $p = .003$, $\eta^2 = .341$, see Figure 4c), and the ODT increase the simulator sickness of VR walking compared to the method Real Walking ($Md = .787, p = .002$).

6 Discussion

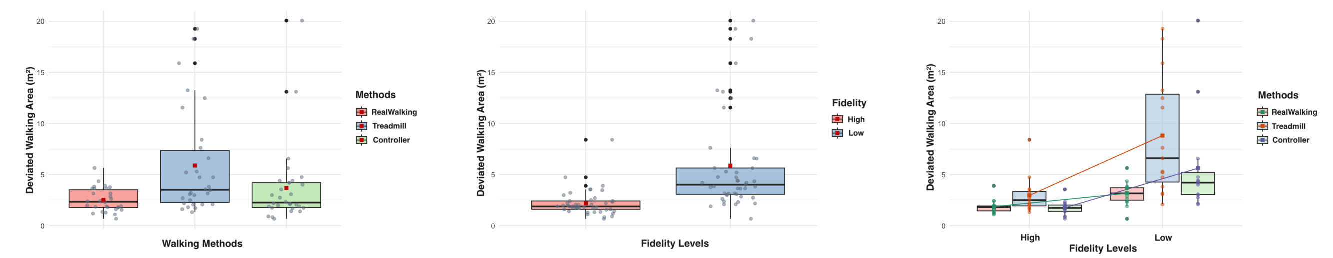
Aiming to investigate the impact of walking methods and levels of fidelity on people's walking experience and performance in VR, we conducted this study to measure participants' dynamic position maintenance during walking with three walking methods (Real Walking, Controller Walking, and the ODT), and in VEs with different levels of fidelity.

6.1 Impact of Different Methods for Walking in VR

From the noteworthy results for the deviated walking areas, it turns out that the evaluation of different walking methods provides a significant influence on the walking experience and performance in VR. The intended effect of walking on an ODT indicated that

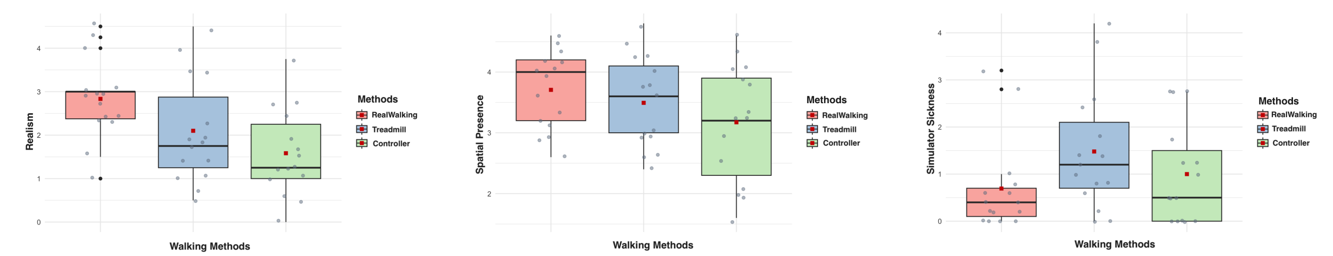
Walking Methods	Position Maintenance (m^2)				VR Experience							
	High Fidelity		Low Fidelity		Involvement		Realism		Presence		Sickness	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Real Walking	1.859	0.687	3.167	1.153	3.217	1.172	2.833	0.939	3.707	0.636	0.693	0.988
Controller	1.750	0.703	5.626	4.796	2.983	1.537	1.583	1.012	3.173	0.953	1.000	1.056
Treadmill	2.957	1.760	8.819	5.816	3.167	1.419	2.100	1.228	3.493	0.744	1.480	1.282

Table 1: Descriptive data results of dynamic position maintenance (difference between the actual and ideal walking areas in square-meter) in walking with different methods under conditions of VEs with high- and low-fidelity, and experience in VR measured with subjective questionnaires IPQ (involvement, realism, spatial presence), and SSQ (simulator sickness).



(a) Difference between actual and ideal walking areas with various walking methods in VR **(b) Difference between actual and ideal walking areas in VR with different levels of fidelity** **(c) The interaction effects of walking methods and fidelity on deviated walking areas in VR**

Figure 3: The figures from (a) to (c) show the data analysis results of deviated walking areas (in squared-meters) in VR affected by walking methods, fidelity, and the interaction effects of independent variables walking methods and levels of fidelity. The larger the deviated walking areas indicate the lower performance of position maintenance in walking.



(a) Realism of walking experience with various methods in VR **(b) Spatial presence of walking experience with various methods in VR** **(c) Simulator sickness of walking with various methods in VR**

Figure 4: The figures from (a) to (c) show the subjective data analysis results of Realism, Spatial Presence, and Simulator Sickness of walking in VR with various walking methods (Real Walking, Controller Walking, and Treadmill).

this locomotion technology highly reduced the performance of dynamic position maintenance in virtual walking compared to the Real Walking method. Previous research indicates that variations in gait between overground and treadmill walking might be attributed to the constraints of treadmill speed and the absence of visual flow [69], more specifically, treadmill walking slowed down the perceived optic flow relative to the walking speed [2, 23]. Consequently, these factors could also contribute to the observed significant differences in dynamic position maintenance of walking on an ODT compared to the Real Walking method.

In the evaluation of walking dynamic position performance, the controller walking also shows a similar impact on position maintenance with the real walking method in walking behavior in VR. Motion sickness is an ongoing issue during the VR experience with HMD, and based on the results from our study, walking with the ODT also significantly aggravates simulator sickness in virtual walking compared to controller walking and real walking. The existing study of Cherni et al. [14] also showed that the sickness symptoms were more intense after using the omnidirectional treadmill than before, and the device caused simulator sickness even after a short exposure. Even though the correlation between simulator sickness and walking performance remains unclear, it is nevertheless worthy to assess the impact of simulator sickness on walking performance and motion stability in VR in future studies. As a revolutionary locomotion technology in VR, the omnidirectional treadmill is an indispensable part of implementing unconstrained movement in large-scale VEs; it's necessary to find a tradeoff between the feasibility of unlimited moving and steady and continuous walking performance, which could optimize the usage of the treadmill in VR to get a higher immersive and stable perception for users.

6.2 Fidelity effects on Walking in VR

According to the result of this study, the levels of visual fidelity also lead to significant differences in the ability of position maintenance during natural walking in VR. The walking performance of dynamic position maintenance was highly increased when people walked in the virtual scenario with high fidelity. Besides, within high-fidelity VE, the influence of different walking methods even have fewer differences in walking performance compared to walking in low-fidelity VE, see Figure 3c. However, in our study, the high-fidelity virtual scenario is implemented within a decorated virtual room, while the low-fidelity scenario is conducted on an open space virtual floor. The enclosed space and walls in the high-fidelity scenario may offer more influential cues for orientation during walking compared to the open space. Therefore, evaluating walking performance in an open-space high-fidelity VE would be another noteworthy research topic in the future. A higher visual fidelity denotes an enhanced capacity to provide more effective visual feedback for stability during the presentation of a stable stimulus [51]. Nevertheless, whether it would have an equivalent effect on walking position maintenance when presenting dynamic stimulus in VEs deserves further investigation. Additionally, interaction fidelity is able to enhance people's performance in VR [49]. Therefore, VEs designed with high fidelity might also improve walking performance in VR, even though the effects might be different across various locomotion methods.

6.3 Measures of Walking Performance in VR

Postural stability is used as an important indicator of people's walking safety in VR. In most existing studies, the balance control of users when moving in VEs is used as the common parameter to investigate the postural stability frequently. Mohebbi et al. [52] also identified users' upright balance control responses to visual inputs in VR to research on maintaining postural stability within complex interactions. However, the two main functional goals of postural behavior are postural orientation and postural equilibrium [28], and postural stability refers to the ability of the position and balance maintenance in the space [56, 79]. Therefore, position maintenance could be another essential index to indicate postural stability when people move in space. The existing research for quantifying driving performance in lane-change tasks [47] measured the deviation between a normative model and the actual course of the subject along the track. Thereby, the area deviation measure indicates driving quality and covers important aspects of the driver's performance, perception, reaction, maneuver, and lane keeping (which all result in an increased deviation). In the context of this study, the walking performance is sensitive to dynamic position maintenance during walking and the capability of dynamic position maintenance, which could also be impacted by distance perception, direction orientation in movement, and the real-time adjustment of the walking path. Consequently, we intended to combine multiple aspects of the factors and measure the deviated area between ideal and actual walking trajectories to evaluate the walking performance. Thus, we see our approach as a novel application of this driving performance measurement in VR. In our study, we found that locomotion technologies can affect working performance in virtual walking, people showed different walking position maintenance when they walked with the real walking method, controller walking method, and the ODT. It's also worth exploring whether the variated performance of dynamic position maintenance in VR could also reveal people's postural stability, more specifically people's balance and position control in the physical world. Additionally, distance is commonly under-perceived in VEs Kelly et al. [33]; the underestimation of the distance might cause disorientation in the perception of the walking path; it's also reasonable to assume that the distance perception affects the performance of the virtual walking. Besides, the starting and stopping delay and offset inherent to controller input and treadmill technologies might also influence the detection and calculation of the dynamic position in virtual walking.

7 Limitations and Future Work

For our experiment, we recruited 15 participants, all of whom are students and belong to a young age demographic. However, compared to young people, older adults showed less stable gait (higher local divergence exponent), the shortest step length, and greater step length variability [45]. Consequently, a larger sample size encompassing a broader range of age demographics would potentially provide a more comprehensive overview of research into walking performance in VR. Additionally, this would also facilitate the evaluation of which walking method would be able to provide a more stable walking behavior for people in various age groups. In the experiment, participants wore an HMD connected to a cable while performing the walking task, which could limit their movement flexibility compared to a wireless connection setup. For further research, implementing a stable wireless connection for the HMD could potentially improve the walking experience in VR.

We assessed people's dynamic position maintenance when they walked with different methods in VEs of varying fidelity levels. This evaluation involved quantifying and comparing the deviation between the actual walking area and the ideal walking area within the VR context. Since walking performance includes multiple parameters, for instance, navigation, gait stability, gait length, and walking speed, a measure involving more parameters would be able to provide a comprehensive evaluation of walking performance in VR. On the other hand, we also found the ODT causes great simulator sickness in virtual walking. However, the ODT is proposed as a promising locomotion approach in large-scale virtual environments to enable users with full freedom of movement in VR. Therefore, it's worth continuing further research on the potential evolution to improve the usability of the omnidirectional treadmill.

8 Conclusion

In this study, we developed walking tasks to investigate the effects of various walking methods (Real Walking, Controller Walking, and omnidirectional treadmill) and fidelity on walking performance and experience in VR. We measured the experience of walking in VR using the dimensions of Realism, Involvement, and Spatial Presence with the IPQ, and Simulator Sickness via the SSQ. We showed that both the walking technique and the different levels of fidelity influence the virtual walking experience and performance. High-fidelity virtual scenarios can improve walking position maintenance with all three methods in VR. Within the same level of VR fidelity, the omnidirectional treadmill impacts the walking experience and performance negatively, people have lower performance of position maintenance and higher simulator sickness when they walk on the omnidirectional treadmill. Additionally, the Real Walking method demonstrated better performance in Realism and Spatial Presence and exhibited the lowest incidence of simulator sickness compared to other walking methods. Virtual environments with high fidelity can also increase walking performance in VR and resist the impact of different locomotion technologies.

References

[1] Domna Banakou and Mel Slater. 2023. A comparison of two methods for moving through a virtual environment: walking in place and interactive redirected walking. *Frontiers in Virtual Reality* 4 (2023), 1294539.

[2] Tom Banton, Jeanine Stefanucci, Frank Durgin, Adam Fass, and Dennis Proffitt. 2005. The Perception of Walking Speed in a Virtual Environment. *Presence: Teleoperators and Virtual Environments* 14, 4 (08 2005), 394–406. https://doi.org/10.1162/105474605774785262 arXiv:https://direct.mit.edu/pvar/article-pdf/14/4/394/1624503/105474605774785262.pdf

[3] C E Bauby and A D Kuo. 2000. Active control of lateral balance in human walking. *J Biomech* 33, 11 (Nov 2000), 1433–1440. https://doi.org/10.1016/s0021-9290(00)00101-9

[4] R H Blanks, C G Fowler, C A Zizz, and K E Williams. 1996. Postural adjustments produced by moving visual (horizontal optokinetic) patterns. *J Am Acad Audiol* 7, 1 (Jan 1996), 39–48.

[5] Corey J. Bohil, Bradly Alicea, and Frank A. Biocca. 2011. Virtual reality in neuroscience research and therapy. *Nature Reviews Neuroscience* 12, 12 (2011), 752–762. https://doi.org/10.1038/nrn3122

[6] Costas Boletsis. 2017. The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology. *Multimodal Technologies and Interaction* 1, 4 (2017). https://doi.org/10.3390/mti1040024

[7] Costas Boletsis and Jarl Erik Cedergren. 2019. VR Locomotion in the New Era of Virtual Reality: An Empirical Comparison of Prevalent Techniques. *Advances in Human-Computer Interaction* 2019, 1 (2019), 7420781. https://doi.org/10.1155/2019/7420781 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1155/2019/7420781

[8] Costas Boletsis, Jarl Erik Cedergren, and Marco Porta. 2019. VR Locomotion in the New Era of Virtual Reality: An Empirical Comparison of Prevalent Techniques. *Adv. in Hum.-Comp. Int.* 2019 (Jan. 2019), 15 pages. https://doi.org/10.1155/2019/7420781

[9] Laroussi Bouguila, Evequoz Florian, Michèle Courant, and Béat Hirsbrunner. 2005. Active Walking Interface for Human-Scale Virtual Environment. In *11th International Conference on Human-Computer Interaction*. HCI International 2005, USA. https://api.semanticscholar.org/CorpusID:14478435

[10] Laroussi Bouguila, Béat Hirsbrunner, Makoto Sato, and Masaru Iwashita. 2003. Virtual Locomotion Interface with Ground Surface Simulation. In *International Symposium on Information, Communication and Automation Technologies*. ICAT 2003, Japan. https://api.semanticscholar.org/CorpusID:15870384

[11] Desiderio Cano Porras, Petra Siemonsma, Rivka Inzelberg, Gabriel Zeilig, and Meir Plotnik. 2018. Advantages of virtual reality in the rehabilitation of balance and gait: Systematic review. *Neurology* 90, 22 (May 2018), 1017–1025. https://doi.org/10.1212/WNL.0000000000005603

[12] Polona Caserman, Augusto Garcia-Agundez, Alvar Gámez Zerban, and Stefan Göbel. 2021. Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. *Virtual Reality* 25 (2021), 1153 – 1170. https://api.semanticscholar.org/CorpusID:234876584

[13] Sarah S. Chance, Florence Gaunet, Andrew C. Beall, and Jack M. Loomis. 1998. Locomotion Mode Affects the Updating of Objects Encountered During Travel: The Contribution of Vestibular and Proprioceptive Inputs to Path Integration. *Presence* 7, 2 (1998), 168–178. https://doi.org/10.1162/105474698565659

[14] Heni Cherni, Souliman Nicolas, and Natacha Métayer. 2021. Using virtual reality treadmill as a locomotion technique in a navigation task: Impact on user experience – case of the KatWalk. *International Journal of Virtual Reality* 21, 1 (May 2021), 1–14. https://doi.org/10.20870/IJVR.2021.21.1.3046

[15] Li-Shan Chou, Kenton R Kaufman, Michael E Hahn, and Robert H Brey. 2003. Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. *Gait Posture* 18, 3 (Dec 2003), 125–133. https://doi.org/10.1016/s0966-6362(02)00067-x

[16] S V Cobb and S C Nichols. 1998. Static posture tests for the assessment of postural instability after virtual environment use. *Brain Res Bull* 47, 5 (Nov 1998), 459–464. https://doi.org/10.1016/s0361-9230(98)00104-x

[17] Susan Valerie Gray Cobb. 1999. Measurement of postural stability before and after immersion in a virtual environment. *Applied Ergonomics* 30, 1 (1999), 47–57. https://doi.org/10.1016/S0003-6870(98)00038-6

[18] Rudolph Darken, Terry Allard, and Lisa Achille. 1999. Spatial Orientation and Wayfinding in Large-Scale Virtual Spaces. *Presence* 8 (12 1999), iii–vi. https://doi.org/10.1162/105474698565604

[19] Rudolph P. Darken, William R. Cockayne, and David Carmein. 1997. The omnidirectional treadmill: a locomotion device for virtual worlds. In *Proceedings of the 10th Annual ACM Symposium on User Interface Software and Technology* (Banff, Alberta, Canada) *(UIST '97)*. Association for Computing Machinery, New York, NY, USA, 213–221. https://doi.org/10.1145/263407.263550

[20] Rudolph P. Darken and John L. Sibert. 1996. Wayfinding strategies and behaviors in large virtual worlds. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, British Columbia, Canada) *(CHI '96)*. Association for Computing Machinery, New York, NY, USA, 142–149. https://doi.org/10.1145/238386.238459

[21] J E Deutsch and A Mirelman. 2007. Virtual reality-based approaches to enable walking for people poststroke. *Top Stroke Rehabil* 14, 6 (Nov-Dec 2007), 45–53. https://doi.org/10.1310/tsr1406-45

[22] Dennis Dietz, Carl Oechsner, Changkun Ou, Francesco Chiossi, Fabio Sarto, Sven Mayer, and Andreas Butz. 2022. Walk This Beam: Impact of Different Balance Assistance Strategies and Height Exposure on Performance and Physiological Arousal in VR. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology* (Tsukuba, Japan) *(VRST '22)*. Association for Computing Machinery, New York, NY, USA, Article 32, 12 pages. https://doi.org/10.1145/3562939.3567818

[23] Frank H Durgin, Krista Gigone, and Rebecca Scott. 2005. Perception of visual speed while moving. *J Exp Psychol Hum Percept Perform* 31, 2 (Apr 2005), 339–353. https://doi.org/10.1037/0096-1523.31.2.339

[24] Rosemary Gallagher, Harish Damodaran, William G Werner, Wendy Powell, and Judith E Deutsch. 2016. Auditory and visual cueing modulate cycling speed of older adults and persons with Parkinson's disease in a Virtual Cycling (V-Cycle) system. *J Neuroeng Rehabil* 13, 1 (Aug 2016), 77. https://doi.org/10.1186/s12984-016-0184-z

[25] David J Harris, Jonathan M Bird, Philip A Smart, Mark R Wilson, and Samuel J Vine. 2020. A Framework for the Testing and Validation of Simulated Environments in Experimentation and Training. *Front Psychol* 11 (2020), 605. https://doi.org/10.3389/fpsyg.2020.00605

[26] 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. https://doi.org/10.1016/j.gaitpost.2006.09.075

[27] John H Hollman, Robert H Brey, Richard A Robb, Tami J Bang, and Kenton R Kaufman. 2006. Spatiotemporal gait deviations in a virtual reality environment. *Gait Posture* 23, 4 (Jun 2006), 441–444. https://doi.org/10.1016/j.gaitpost.2005.05.005

[28] Fay B Horak. 2006. Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age Ageing* 35 Suppl 2 (Sep 2006), ii7–ii11. https://doi.org/10.1093/ageing/afl077

[29] Hanne Huygelier, Emily Mattheus, Vero Vanden Abeele, Raymond van Ee, and Céline R Gillebert. 2021. The Use of the Term Virtual Reality in Post-Stroke Rehabilitation: A Scoping Review and Commentary. *Psychol Belg* 61, 1 (Jun 2021), 145–162. https://doi.org/10.5334/pb.1033

[30] Hiroo Iwata. 1999. The Torus Treadmill: Realizing Locomotion in VEs. *IEEE Comput. Graph. Appl.* 19, 6 (nov 1999), 30–35. https://doi.org/10.1109/38.799737

[31] Omar Janeh and Frank Steinicke. 2021. A Review of the Potential of Virtual Walking Techniques for Gait Rehabilitation. *Front Hum Neurosci* 15 (2021), 717291. https://doi.org/10.3389/fnhum.2021.717291

[32] Grzegorz Juras, Anna Brachman, Justyna Michalska, Anna Kamieniarz, Michał Pawłowski, Anna Hadamus, Dariusz Białoszewski, Janusz Błaszczyk, and Kajetan J Słomka. 2019. Standards of Virtual Reality Application in Balance Training Programs in Clinical Practice: A Systematic Review. *Games Health J* 8, 2 (Apr 2019), 101–111. https://doi.org/10.1089/g4h.2018.0034

[33] Jonathan W. Kelly, Lucia A. Cherep, Brenna Klesel, Zachary D. Siegel, and Seth George. 2018. Comparison of Two Methods for Improving Distance Perception

in Virtual Reality. *ACM Trans. Appl. Percept.* 15, 2, Article 11 (mar 2018), 11 pages. https://doi.org/10.1145/3165285

[34] Robert S. Kennedy, Norman E. Lane, Michael G. Lilienthal, Kevin S. Berbaum, and Lawrence J. Hettinger. 1992. Profile Analysis of Simulator Sickness Symptoms: Application to Virtual Environment Systems. *Presence: Teleoperators and Virtual Environments* 1, 3 (08 1992), 295–301. https://doi.org/10.1162/pres.1992.1.3.295 arXiv:https://direct.mit.edu/pvar/article-pdf/1/3/295/1622384/pres.1992.1.3.295.pdf

[35] Adam W. Kiefer, Christopher K. Rhea, and William H. Warren. 2013. *VR-Based Assessment and Rehabilitation of Functional Mobility.* Springer New York, New York, NY, 333–350. https://doi.org/10.1007/978-1-4419-8432-6_15

[36] Deog Young Kim and Jong Bum Park. 2013. Virtual reality based stroke rehabilitation. *Journal of the Korean Medical Association/Taehan Uisa Hyophoe Chi* 56, 1 (2013), 16–22.

[37] Yusuke Koseki and Tomohiro Amemiya. 2024. Being an older person: modulation of walking speed with geriatric walking motion avatars. *Frontiers in Virtual Reality* 5 (2024). https://doi.org/10.3389/frvir.2024.1363043

[38] David E Krebs, Dov Goldvasser, Joyce D Lockert, Leslie G Portney, and Kathleen M Gill-Body. 2002. Is base of support greater in unsteady gait? *Phys Ther* 82, 2 (Feb 2002), 138–147. https://doi.org/10.1093/ptj/82.2.138

[39] Jiwon Lee, Mingyu Kim, and Jinmo Kim. 2017. A Study on Immersion and VR Sickness in Walking Interaction for Immersive Virtual Reality Applications. *Symmetry* 9, 5 (2017). https://doi.org/10.3390/sym9050078

[40] Huey-Wen Liang, Shao-Yu Chi, Bo-Yuan Chen, Yue-Hua Li, Tzu-Ling Tai, and Yaw-Huei Hwang. 2021. The Effects of Visual Backgrounds in the Virtual Environments on the Postural Stability of Standing. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 29 (2021), 1129–1137. https://doi.org/10.1109/TNSRE.2021.3087021

[41] Robert W. Lindeman and Steffi Beckhaus. 2009. Crafting memorable VR experiences using experiential fidelity. In *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology* (Kyoto, Japan) *(VRST '09)*. Association for Computing Machinery, New York, NY, USA, 187–190. https://doi.org/10.1145/1643928.1643970

[42] B.-B Liu, Q.-N Ding, and W.-S Zhu. 2018. Research progress on the role of virtual reality technology in rehabilitation of nervous system diseases. *Chinese Journal of Contemporary Neurology and Neurosurgery* 18 (03 2018), 222–225. https://doi.org/10.3969/j.issn.1672-6731.2018.03.012

[43] Jesse Lohman and Luca Turchet. 2022. Evaluating Cybersickness of Walking on an Omnidirectional Treadmill in Virtual Reality. *IEEE Transactions on Human-Machine Systems* 52, 4 (2022), 613–623. https://doi.org/10.1109/THMS.2022.3175407

[44] Carlos Luque-Moreno, Alejandro Ferragut-Garcías, Cleofás Rodríguez-Blanco, Alberto Marcos Heredia-Rizo, Jesús Oliva-Pascual-Vaca, Pawel Kiper, and Ángel Oliva-Pascual-Vaca. 2015. A Decade of Progress Using Virtual Reality for Post-stroke Lower Extremity Rehabilitation: Systematic Review of the Intervention Methods. *Biomed Res Int* 2015 (2015), 342529. https://doi.org/10.1155/2015/342529

[45] Rina M. Magnani, Sjoerd M. Bruijn, Jaap H. van Dieën, and Marcus F. Vieira. 2020. Head orientation and gait stability in young adults, dancers and older adults. *Gait & Posture* 80 (2020), 68–73. https://doi.org/10.1016/j.gaitpost.2020.05.035

[46] B E Maki. 1997. Gait changes in older adults: predictors of falls or indicators of fear. *J Am Geriatr Soc* 45, 3 (Mar 1997), 313–320. https://doi.org/10.1111/j.1532-5415.1997.tb00946.x

[47] Stefan Mattes. 2003. The lane-change-task as a tool for driver distraction evaluation. *Quality of Work and Products in Enterprises of the Future* 57, 60 (2003), 7.

[48] Morgan McCullough, Hong Xu, Joel Michelson, Matthew Jackoski, Wyatt Pease, William Cobb, William Kalescky, Joshua Ladd, and Betsy Williams. 2015. Myo arm: swinging to explore a VE. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception* (Tübingen, Germany) *(SAP '15)*. Association for Computing Machinery, New York, NY, USA, 107–113. https://doi.org/10.1145/2804408.2804416

[49] Ryan P. McMahan, Doug A. Bowman, David J. Zielinski, and Rachael B. Brady. 2012. Evaluating Display Fidelity and Interaction Fidelity in a Virtual Reality Game. *IEEE Transactions on Visualization and Computer Graphics* 18, 4 (2012), 626–633. https://doi.org/10.1109/TVCG.2012.43

[50] Hylton B Menz, Stephen R Lord, and Richard C Fitzpatrick. 2003. Age-related differences in walking stability. *Age Ageing* 32, 2 (Mar 2003), 137–142. https://doi.org/10.1093/ageing/32.2.137

[51] R. J. Menzies, S. J. Rogers, A. M. Phillips, E. Chiarovano, C. de Waele, F. A. J. Verstraten, and H. MacDougall. 2016. An objective measure for the visual fidelity of virtual reality and the risks of falls in a virtual environment. *Virtual Reality* 20, 3 (2016), 173–181. https://doi.org/10.1007/s10055-016-0288-6

[52] Abolfazl Mohebbi, Pouya Amiri, and Robert E. Kearney. 2022. Identification of human balance control responses to visual inputs using virtual reality. *Journal of Neurophysiology* 127, 4 (2022), 1159–1170. https://doi.org/10.1152/jn.00283.2021 arXiv:https://doi.org/10.1152/jn.00283.2021 PMID: 35353629.

[53] Francisco Nieto-Escamez, Irene Cortés-Pérez, Esteban Obrero-Gaitán, and Augusto Fusco. 2023. Virtual Reality Applications in Neurorehabilitation: Current Panorama and Challenges. *Brain Sciences* 13, 5 (2023), 819. https://doi.org/10.3390/brainsci13050819

[54] Niels C. Nilsson, Stefania Serafin, Morten H. Laursen, Kasper S. Pedersen, Erik Sikström, and Rolf Nordahl. 2013. Tapping-In-Place: Increasing the naturalness of immersive walking-in-place locomotion through novel gestural input. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, Orlando, FL, USA, 31–38. https://doi.org/10.1109/3DUI.2013.6550193

[55] Niels Christian Nilsson, Stefania Serafin, Frank Steinicke, and Rolf Nordahl. 2018. Natural Walking in Virtual Reality: A Review. *Comput. Entertain.* 16, 2, Article 8 (apr 2018), 22 pages. https://doi.org/10.1145/3180658

[56] Manfred Nusseck and Claudia Spahn. 2020. Comparison of Postural Stability and Balance Between Musicians and Non-musicians. *Front Psychol* 11 (2020), 1253. https://doi.org/10.3389/fpsyg.2020.01253

[57] Marousa Pavlou, Catherine Quinn, Kate Murray, Chrysa Spyridakou, Mary Faldon, and Adolfo M Bronstein. 2011. The effect of repeated visual motion stimuli on visual dependence and postural control in normal subjects. *Gait Posture* 33, 1 (Jan 2011), 113–118. https://doi.org/10.1016/j.gaitpost.2010.10.085

[58] Benito Peñasco-Martín, Ana de los Reyes-Guzmán, Ángel Gil-Agudo, Alberto Bernal-Sahún, Beatriz Pérez-Aguilar, and Ana Isabel de la Peña-González. 2010. [Application of virtual reality in the motor aspects of neurorehabilitation]. *Rev Neurol* 51, 8 (Oct 2010), 481–488.

[59] Giuseppe Placidi, Danilo Avola, Marco Ferrari, Daniela Iacoviello, Andrea Petracca, Valentina Quaresima, and Matteo Spezialetti. 2014. A low-cost real time virtual system for postural stability assessment at home. *Comput Methods Programs Biomed* 117, 2 (Nov 2014), 322–333. https://doi.org/10.1016/j.cmpb.2014.06.020

[60] Lisa Reichl and Martin Kocur. 2024. Investigating the Impact of Odors and Visual Congruence on Motion Sickness in Virtual Reality. In *Proceedings of the 30th ACM Symposium on Virtual Reality Software and Technology* (Trier, Germany) *(VRST '24)*. Association for Computing Machinery, New York, NY, USA, Article 25, 12 pages. https://doi.org/10.1145/3641825.3687731

[61] Jason T. Richards, Ajitkumar P. Mulavara, and Jacob J. Bloomberg. 2004. Postural Stability During Treadmill Locomotion as a Function of the Visual Polarity and Rotation of a Three-Dimensional Virtual Environment. *Presence* 13, 3 (2004), 371–384. https://doi.org/10.1162/1054746041422299

[62] S Roeles, P J Rowe, S M Bruijn, C R Childs, G D Tarfali, F Steenbrink, and M Pijnappels. 2018. Gait stability in response to platform, belt, and sensory perturbations in young and older adults. *Med Biol Eng Comput* 56, 12 (Dec 2018), 2325–2335. https://doi.org/10.1007/s11517-018-1855-7

[63] B. Schaeffer and C. Goudeseune. 2003. Syzygy: native PC cluster VR. In *IEEE Virtual Reality, 2003. Proceedings.* IEEE, Los Angeles, CA, USA, 15–22. https://doi.org/10.1109/VR.2003.1191116

[64] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The Experience of Presence: Factor Analytic Insights. *Presence: Teleoperators and Virtual Environments* 10, 3 (06 2001), 266–281. https://doi.org/10.1162/105474601300343603 arXiv:https://direct.mit.edu/pvar/article-pdf/10/3/266/1623697/105474601300343603.pdf

[65] Philipp Schuhbauer, Laurin Muth, Julia Grötsch, Johannes Wiesneth, Johannes Dengler, Martin Kocur, and Michael Lankes. 2019. Hover Loop: A New Approach to Locomotion in Virtual Reality. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts* (Barcelona, Spain) *(CHI PLAY '19 Extended Abstracts)*. Association for Computing Machinery, New York, NY, USA, 111–116. https://doi.org/10.1145/3341215.3356984

[66] Robert Shewaga, Alvaro Uribe-Quevedo, Bill Kapralos, and Fahad Alam. 2020. A Comparison of Seated and Room-Scale Virtual Reality in a Serious Game for Epidural Preparation. *IEEE Transactions on Emerging Topics in Computing* 8, 1 (2020), 218–232. https://doi.org/10.1109/TETC.2017.2746085

[67] Martin Simoneau, Normand Teasdale, Christophe Bourdin, Chantal Bard, Michelle Fleury, and Vincent Nougier. 1999. Aging and Postural Control: Postural Perturbations Caused by Changing the Visual Anchor. *Journal of the American Geriatrics Society* 47, 2 (1999), 235–240. https://doi.org/10.1111/j.1532-5415.1999.tb04584.x arXiv:https://agsjournals.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1532-5415.1999.tb04584.x

[68] Mel Slater. 2002. Presence and The Sixth Sense. *Presence: Teleoperators and Virtual Environments* 11, 4 (08 2002), 435–439. https://doi.org/10.1162/105474602760204327 arXiv:https://direct.mit.edu/pvar/article-pdf/11/4/435/1623799/105474602760204327.pdf

[69] L.H. Sloot, M.M. van der Krogt, and J. Harlaar. 2014. Effects of adding a virtual reality environment to different modes of treadmill walking. *Gait & Posture* 39, 3 (2014), 939–945. https://doi.org/10.1016/j.gaitpost.2013.12.005

[70] Kay M Stanney and Robert S Kennedy. 2010. *Simulation sickness.* ed Boca Raton, Florida: CRC Press, USA.

[71] Nigel W. Tierney, Jessica R. Crouch, Hector M. Garcia, Martha L Walker, Bonnie L. Van Lunen, Gianluca DeLeo, George C Maihafer, and Stacie I. Ringleb. 2007. Virtual Reality in Gait Rehabilitation. *Engineering, Medicine* 6, 6 (2007). https://api.semanticscholar.org/CorpusID:18998313

[72] Martin Usoh, Kevin Arthur, Mary C. Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P. Brooks. 1999. Walking > walking-in-place > flying, in virtual environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '99)*. ACM Press/Addison-Wesley Publishing Co., USA, 359–364. https://doi.org/10.1145/311535.311589

[73] M G Wade and G Jones. 1997. The role of vision and spatial orientation in the maintenance of posture. *Phys Ther* 77, 6 (Jun 1997), 619–628. https://doi.org/10.1093/ptj/77.6.619

[74] Xinyuan Wang, Jifang Qiu, Yuda Zhou, Wenbing Liu, Shuijing Zhang, Yichen Gong, Wei Jiang, Linjie Fang, Changmeng Ji, Xin Yao, Weiqiang Wang, Sihui Xu, Zhouzhou Lu, and Yong Ding. 2024. Effects of Virtual Reality–Assisted and Overground Gait Adaptation Training on Balance and Walking Ability in Stroke Patients: A Randomized Controlled Trial. *American Journal of Physical Medicine & Rehabilitation* 103, 6 (2024). https://journals.lww.com/ajpmr/fulltext/2024/06000/effects_of_virtual_reality_assisted_and_overground.3.aspx

[75] Yu Wang, Jakob Eckkrammer, Martin Kocur, and Philipp Wintersberger. 2024. Investigation of Simulator Sickness in Walking with Multiple Locomotion Technologies in Virtual Reality. In *Proceedings of the 30th ACM Symposium on Virtual Reality Software and Technology* (Trier, Germany) *(VRST '24)*. Association for Computing Machinery, New York, NY, USA, Article 78, 2 pages. https://doi.org/10.1145/3641825.3689686

[76] Mark Ward, Ronald Azuma, Robert Bennett, Stefan Gottschalk, and Henry Fuchs. 1992. A demonstrated optical tracker with scalable work area for head-mounted display systems. In *Proceedings of the 1992 Symposium on Interactive 3D Graphics* (Cambridge, Massachusetts, USA) *(I3D '92)*. Association for Computing Machinery, New York, NY, USA, 43–52. https://doi.org/10.1145/147156.147162

[77] M.C. Whitton, J.V. Cohn, J. Feasel, P. Zimmons, S. Razzaque, S.J. Poulton, B. McLeod, and F.P. Brooks. 2005. Comparing VE locomotion interfaces. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.* IEEE, Bonn, Germany, 123–130. https://doi.org/10.1109/VR.2005.1492762

[78] Preston Tunnell Wilson, William Kalescky, Ansel MacLaughlin, and Betsy Williams. 2016. VR locomotion: walking > walking in place > arm swinging. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry - Volume 1* (Zhuhai, China) *(VRCAI '16)*. Association for Computing Machinery, New York, NY, USA, 243–249. https://doi.org/10.1145/3013971.3014010

[79] Marjorie Woollacott and Anne Shumway-Cook. 2002. Attention and the control of posture and gait: a review of an emerging area of research. *Gait & Posture* 16, 1 (2002), 1–14. https://doi.org/10.1016/S0966-6362(01)00156-4

[80] David J. Zielinski, Ryan P. McMahan, and Rachael B. Brady. 2011. Shadow walking: An unencumbered locomotion technique for systems with under-floor projection. In *2011 IEEE Virtual Reality Conference*. IEEE, Singapore, 167–170. https://doi.org/10.1109/VR.2011.5759456