The Impact of Avatar Appearance, Perspective and Context on Gait Variability and User Experience in Virtual Reality

Markus Wirth*
Machine Learning & Data Analytics,
Univ. of Erlangen-Nürnberg (FAU)
Erlangen, Germany

Stefan Gradl †
Machine Learning & Data Analytics,
Univ. of Erlangen-Nürnberg (FAU)
Erlangen, Germany

Georg Prosinger ‡
Machine Learning & Data Analytics,
Univ. of Erlangen-Nürnberg (FAU)
Erlangen, Germany

Felix Kluge §
Machine Learning & Data Analytics,
Univ. of Erlangen-Nürnberg (FAU)
Erlangen, Germany

Daniel Roth ¶
Chair of Computer Aided
Medical Procedures
TUM, Munich, Germany

Bjoern M. Eskofier ‖
Machine Learning & Data Analytics,
Univ. of Erlangen-Nürnberg (FAU)
Erlangen, Germany

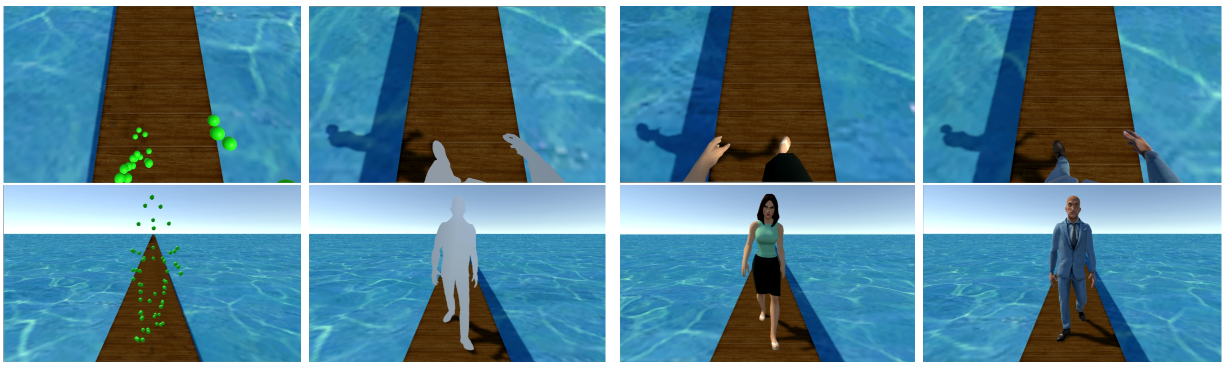


Figure 1: Illustration of the different egocentric avatar representations from a first person and frontal perspective. From left to right the pointcloud (PTC) followed by the sillhouette (SIL) and humanoid (HUM) user representation is shown.

Abstract

Gait supervision plays an important role in the diagnosis, analysis and rehabilitation of motor impairments and neurodegenerative disorders. For example, in Parkinson's disease, gait assessment is used for progression observation and medication guidance. Previous work has presented the potential of virtual reality (VR) supported gait applications. While virtual environments and user representation strategies are used for gait applications, the influence of appearance and context cues on gait performance is not extensively researched. In this paper, we analyzed the influence of avatar appearance, environment awareness, and camera perspective on gait parameters relevant for clinical application. Four different avatar appearances, varying in abstraction, two environmental settings, as well as an egocentric and exocentric camera perspective were compared in three walking tasks on a treadmill. Our results show that variability, as an indicator for gait stability, is significantly impacted by VR exposure in comparison to a real world (in vivo) baseline. Further, our results revealed that walking tasks influence gait behavior significantly different in VR compared to in vivo. Overall, these findings suggest that particular care has to be taken when assessing gait characteristics acquired from subjects immersed in VR and that equivalence of results with in vivo may not be blindly assumed.

*e-mail: markus.wirth@fau.de
†e-mail: stefan.gradl@fau.de
‡e-mail: georg.prosinger@fau.de
§e-mail: felix.kluge@fau.de
¶e-mail: daniel.roth@tum.de
‖e-mail: bjoern.eskofier@fau.de

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Virtual reality

1 Introduction

Gait analysis is a well-established tool in the clinical environment to quantify and objectively describe human walking movement, which assists in the diagnosis and treatment decision-making processes for diseases such as stroke, cerebral palsy, and Parkinson's disease, where gait behavior reflects progression and severity [51, 53, 63, 67].

Recent technological developments led to significant advances in ubiquitous and objectified gait analysis using wearable sensors [13, 14]. Besides wearable sensors, virtual reality (VR) has become increasingly popular in terms of gait analysis and treatment in research, as it allows to display immersive controllable environments to design individual training and treatment programs [2, 11, 29, 50]. This has sparked much research that proved the effectiveness of rehabilitation measures in VR for motor impairments and neurodegenerative diseases [22, 23, 61].

VR is a promising tool to ease the scientific analysis of human behavior [4, 20, 64, 65]. With the precise control over the delivery of stimuli, the environment and the simulation itself, a repeatability of experiments can be achieved that is otherwise not possible with similar efforts. For example, researchers used gait scenarios on treadmills to show that rehabilitation effects for virtual environment (VE) based training and in vivo training are comparable [8, 43].

However, training methods in VR are often transferred from the real world without considering effects of immersion on the user. Furthermore, traditional laboratory tests rely on using analogue measurements (e.g. employing a stop-watch), which is not necessary in a VE and can thus be done much more accurately. It is well known that spatiotemporal gait parameters and their variability are susceptible to even slight inaccuracies in the measurement. Thus they should also be considered when comparing different gait tests in VR and

2642-5254/21/$31.00 ©2021 IEEE
DOI 10.1109/VR50410.2021.00055

in vivo [9, 33, 38]. Contrary to expectations, this is rarely the case in the literature regarding VR gait training and analysis. Specifically, it is not well understood how distinct aspects of the simulation, such as the appearance of the virtual self-representation (i.e. avatar embodiment [54]), the context cues presented in the VE, or the camera perspective used for the simulation impact spatiotemporal gait parameters.

The present work therefore provides further insights into the changes of gait characteristics in VEs in dependency of these presentation properties and in comparison to in vivo gait performance. These insights are specifically important for VR supported gait rehabilitation and assessment, since they outline more detailed considerations to be made when designing VEs for such purposes.

1.1 Contribution

In this paper, we assess differences between gait variability in VR compared to an in vivo situation in relation to different walking tasks. We further contribute by evaluating three factors that could potentially impact gait stability in VR, namely the avatar appearance, the virtual camera perspective, and the environmental cues presented to the user. Our findings show differences between VR and in vivo depending on the walking task. Overall, the results of this research work suggest differences between physical and virtual application, and are therefore of importance to VR supported gait application developments as well as clinicians.

2 Background and Related Work

2.1 Avatar Appearance in VE

There is a variety of research showing the impact of avatar appearance on user behavior resulting in significant knowledge regarding the effect of psychophysical aspects on users' immersion and presence.

Several studies explored the influence of altered avatar representations to understand how aspects like gender [35, 58], age [3, 52], anthropomorphism [37], and skin color [1, 48] change the user's self-perception [54] and provoke a change in user behavior and attitude, according to the "Proteus Effect" [68]. As an example Reinhard et al. investigated the effect of avatar age on post-embodiment walking speed. Their results could show that participants being embodied with older avatars spent a significantly longer time on walking a set distance compared to the group experiencing a young avatar self-representation [52].

Other studies in the area of avatar appearance focus on examining the sense of body ownership [7, 45, 54, 55, 59]. It describes the sense of self-attribution to a virtual body and is, to part, dependent on specific conditions and stimuli like the degree of visuomotor alignment between physical movement and its virtual representation [60]. In a recent study Ogawa et al. for example could show that representation by a realistic full-body self-avatar encouraged participants to accept and consider physical boundaries also in a VE [46]. Therefore, they explored different levels of avatar anthropomorphism and its effect on the participants willingness to walk through digital walls. Results could show that participants experiencing a lower presence tended to walk through walls sooner and that a realistic avatar representation is beneficial for discouraging participants to walk through walls.

In summary, there has been some previous research in the are of avatar representation, however there is only few work that researches its influence on clinical relevant measures like spatiotemporal parameters in gait analysis.

2.2 Gait Analysis in VR

VR based clinical gait analysis is applied in different areas where gait behavior is known to be an important indicator for the progression and extent of a disease. In case of neurodegenerative diseases, previous work could show that gait analysis in VR can be used to address deficits associated with fall risk of Parkinson's patients [2, 29, 40]. Results of the studies indicate that training using different visual feedback in VR can reduce fall risk of patients. Therefore, relevant gait parameters were evaluated like gait stability, walking speed, and stride length. Moreover an enhancement in cognitive functions for patients could be observed when training in VR [44].

Beyond the medical scope, multiple work considered different aspects of walking in VR. The effect of isometric and non-isometric walking in VEs and its influence on self-motion and biomechanical walking parameters were investigated [29–31, 42]. Results of these studies are not clear. Some research outcomes suggest that participants perceive a slightly increased virtual speed and hence non-isometric walking as more natural [42]. Contrary, other studies could not underpin these findings, but propose that the highest correlation between real and virtual world walking is achieved by isometric mapping. These studies could also observe symmetrical detriments for non-isometric mappings when increasing or decreasing virtual walking velocity [29–31].

Further, research focused on investigating the differences of participants' gait between VR and real world conditions. In a study conducted by Canessa et al., they used a head-mounted display (HMD) and controllers attached to the feet to investigate the difference in real world and virtual walking. Their derived spatiotemporal gait measures did not result in differences between VR and non-VR walking [6]. Opposing, earlier work from Hollman et al. [26, 27] examined the effect of VR on spatiotemporal gait parameters and their variability using a hemispherical screen in front of a treadmill. Results suggest a higher variation of gait parameters for the VR compared to the non-VR condition.

Consequently, previous introduced work in this area mainly focuses on the actual effect of a specific treatment in VR or investigates its correlation to real world walking. However, it is not yet very well known how specific characteristics of the VE influence gait parameters relevant for clinical assessments. Gaining deeper knowledge on how VR as a medium itself, the context of a VE, and the representation of the user affects gait behavior contributes to improve and increase efficiency of VR based gait analysis. Therefore, the aim of this work is to create a deeper understanding of how characteristics of a VE influence human gait behavior.

In a user study, we compared differences in variability of spatiotemporal gait parameters (i.e. stride length and time, step width) for a VR and contrasting physical condition, as well as modified VR visualizations in terms of context, avatar appearance and perspective in relation to three different walking tasks.

3 Materials and Methods

We conducted a repeated-measures study to assess the impacts of individual factors. 18 participants were equipped with a marker set and asked to walk on a treadmill, wearing a HMD in the VR conditions. In each condition, participants had to do three walking tasks focusing their attention to different view directions (down, straight, and looking around in the environment). To compare the impact of the *medium*, an in vivo baseline assessment was taken as well as the equivalent VR condition. To compare the impact of *perspective*, participants were asked to perform VR conditions in an egocentric as well as exocentric simulation perspective. To explore the factor *context*, supplementary visual cues were given to the participants in an egocentric perspective. Further, four different egocentric avatar representations were used to assess the impact of *avatar appearance*.

3.1 Apparatus

The laboratory setup allowed unlimited walking on an instrumented treadmill (Bertec Corporation, Columbus, OH, USA) surrounded by a marker-based optical motion capture system (Fig. 2, Qualisys AB, Gothenburg, Sweden). The system comprised eight Oqus 300 cameras and one Oqus 100 camera, each sampling infrared images

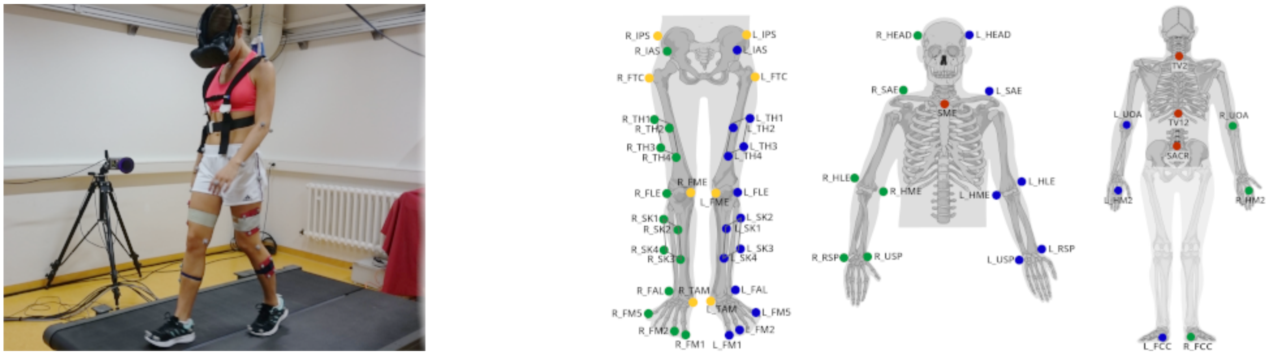


Figure 2: Left: Gait laboratory with a participant walking on the treadmill in virtual reality. Right: Illustration of the applied standardized anatomical marker placement [62] for full body motion capturing.

of marker reflections at 200 Hz. The applied standardized marker setup consisted of 59 reflective passive markers attached to relevant anatomical points on the full body [62]. The captured data was recorded and streamed via network to map the motion to an avatar in real-time. The visualization was displayed to the user utilizing a HMD and a VE rendered by an external processing unit. The system delay was not measured continuously, but most of the time no delay was noticeable by the participants during the experiment. In some rare cases the system lost track of the head markers for a split second, causing a short lag. Such phases were discarded in the recording. Participants were secured with a rope harness fixed on the ceiling against falling.

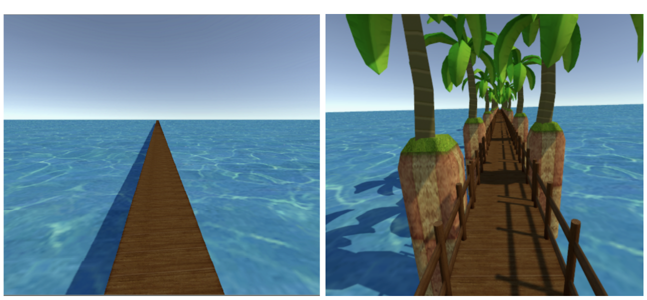
3.1.1 Virtual Environment

For displaying the VE a first generation HTC Vive was used with room scale tracking set up in parallel to the motion capture system. The VR system consists of an HMD with a resolution of 1080x1200 pixels for each eye.

The VE mainly comprised an infinite jetty surrounded by water (Fig. 3a). This design was chosen to allow participants to focus on the walking tasks and to compensate the limited space of the treadmill. To further be able to also explore the influence of additional visual references, we created a second extended environment (Fig. 3b). It is enhanced by additional visual cues in form of a rail and palm trees evenly arranged on both sides of the jetty.

3.1.2 User Representation

To provide different avatar representations to the user, the HMD was wired to a PC that received, processed and displayed the motion



(a) (b)

Figure 3: The infinite walking environment (a) comprising a infinity jetty walkway over water, and the enhanced environment (b) including additional visual cues.

capture data using the Unity3D Engine[1]. The motion input for avatar embodiment was provided by the motion capture system, while the VR perspective was provided by the HMD tracking system. This was manually calibrated for overlap at the beginning of each data recording session and worked reasonably well so that participants could not discern that tracking was facilitated by two independent systems. The mapping of marker points through the motion capture system to the skeleton of the virtual avatar was done with the help of a pre-made Qualisys plugin for Unity3D [2]. This allowed an exact and size corrected avatar mapping.

To create different avatars, we oriented our design towards anthropomorphism. It is defined as the attribution of human-like properties or characteristics to real or imagined non-human avatars and objects [36]. Anthropomorphism includes the aspects anatomy and composition. The latter describes the specific design of body parts like shape, scale and texture. The anatomical aspect focuses on the general structural information of the number and type of body parts visualized [12]. On the base of this design space we created four egocentric avatars that vary in the level of avatar representation. To further investigate how the sense of self-location impacts gait, we also designed an exocentric perspective [5, 46].

3.2 Conditions

For the conducted study different conditions were assessed. This included different VR conditions (Figure 1) as well as the natural gait of the participants.

In Vivo Baseline (in vivo)

To provide a reference for the VR gait conditions a baseline measurement was acquired. The baseline measurement was based on the natural gait of the participants without any HMD or other additional material. Data was collected while participants walked on the treadmill for one minute.

No Avatar (NoVis)

To explore the impact of no visual references on participants' gait, we created the NoVis condition. It is characterized by no body parts being visualized. Hence, participants did not experience any visual references of their body during walking.

Pointcloud (PTC)

For this condition only the marker positions were represented as small green spheres. The participants did not see their limbs but only these spherical representations on key landmarks. Figure 1 shows the representation from an outside and egocentric view.

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

[2]https://www.qualisys.com/software/unity

Silhouette (SIL)

The limbs are represented as a simplified and colorless visualization of real limbs. The representation is comparable with bright outlines. Figure 1 also illustrates this user representation.

Humanoid (HUM)

For this type of representation the participants got either a male or a female character assigned, depending on their in vivo gender association. The male representation is a detailed model of a middle-aged business man, wearing a blue suit. The female representation is a business woman, wearing a black skirt and a green top (Fig. 1). The clothes for the models were chosen, to allow the participants to better identify with a gender specific model [32]. Both avatars, female [3] and male [4], are freely available in the Unity Asset Store.

Exocentric (EXO)

The exocentric visualization was presented in addition to the four visualizations explained above. For this exocentric perspective the participant saw the humanoid avatar representation with the camera placed slightly behind and above the character (Fig. 4). Hence, participants experienced their avatar from a distant out-of-body perspective.

Environment (HUM + ENV)

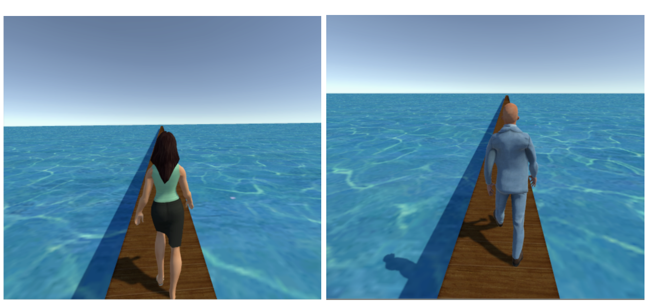
To investigate the influence of context in VR, the standard environment (see section 3.1.1) was enhanced by additional visual cues. The difference to the standard environment are additional reference points in the form of a railing and equidistantly aligned palm trees (Fig. 3). Participants experienced this condition being represented by the humanoid avatar representation. To compare the differences in context, gait behavior within the standard environment with a humanoid avatar (HUM) was compared to this enhanced environment (HUM + ENV).

3.3 Participants

A total of 18 participants (7 female, 11 male) took part in the study. The average age of participants was $M = 22.9$ ($SD = 2.4$) years and the average BMI was $M = 22.1$ ($SD = 1.6$). Nearly half of the participants had eye problems and needed glasses or used contact lenses. Five participants had previous VR experience. None of the participants had physical restrictions or impairments. The experience of the participants in walking on a treadmill varied. Eleven never walked on a treadmill before, while four (22%) are on a treadmill several times per year and three (17%) once a year or less. Six participants play video games regularly (33%), four play at least once a year (22%) and eight never played video games before (44%). None of the participants suffered from aquaphobia which could have affected gait in this particular VR setting.

[3]https://assetstore.unity.com/packages/3d/characters/humanoids/modern-female-professional-secretary-44429

[4]https://assetstore.unity.com/packages/3d/characters/humanoids/man-in-a-suit-51662



(a) (b)

Figure 4: Illustration of the different exocentric representations for female (a) and male (b) participants.

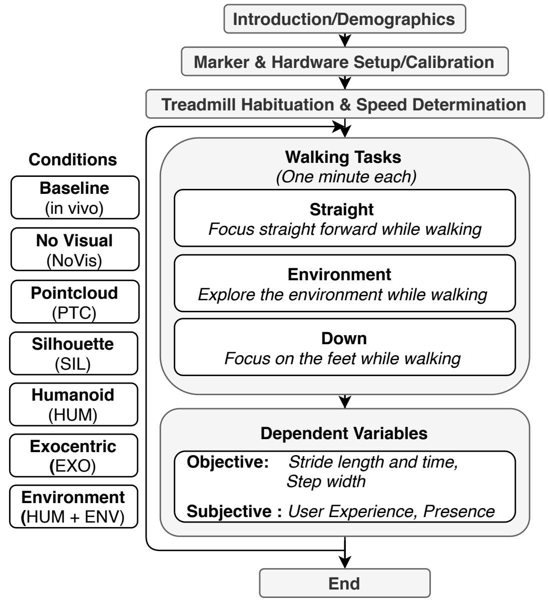


Figure 5: Overview of the study procedure.

3.4 Measures

We evaluated objective gait measures of the participants based on optical motion capture. To evaluate subjective perception we measured participants' user experience including presence.

3.4.1 Gait Parameters

For all participants, the stride length, stride time and step width were measured by means of the motion capture system. As proposed by Perry et al., we defined a stride as the interval between two sequential initial floor contacts of the same limb [49]. Stride length was defined as the distance between the subsequent proximal end positions of one foot. Step width was defined as medio-lateral distances between the proximal end position of the contralateral feet. Gait stability was determined by considering the coefficient of variation (COV, defined as ratio of standard deviation and mean multiplied by 100) for these parameters.

3.4.2 User Experience

To evaluate the user experience of participants, we used the AttrakDiff questionnaire [24]. It consists of 28 items described by semantic differentials with a 7-point Likert scale. The questionnaire measures the different subcategories pragmatic quality (PQ), attractiveness (ATT) as well as the hedonic qualities of identification (HQ_I) and stimulation (HQ_S).

3.4.3 Presence

A revised version by the UQO Cyberpsychology Lab (2004) of the Witmer and Singer presence questionnaire was applied to measure the presence of participants after each walking trial [34, 66]. This questionnaire consists of 19 items with a 7-point Likert scale. Each item includes semantic differentials. The items of the questionnaire can be collapsed into the five subcategories realism, possibility to act (PossToAct), quality of interface (Interface), possibility to examine (PossExam) and self-evaluation of performance (Performance).

3.5 Procedure

Before conducting the study, the Qualisys Motion Capture and the HTC Vive system were calibrated. Also the marker set, the Unity project, the treadmill and the QTM marker model were prepared. At the beginning of the study participants were welcomed and the study was explained. Then participants were asked to fill out a consent form and to answer a demographic and health questionnaire.

Next, the participants were equipped with a safety chest harness and a safety-rope attached to the ceiling to prevent any possible injuries. Next, the 59 reflective markers were attached to the participants (Fig. 2). Then, the treadmill speed was calibrated to match the individual participant's normal comfortable walking speed on the treadmill. The speed was slowly increased from 0.6 to 1.4 m/s or until the participant indicated to experience a comfortable speed for regular walking.

While walking on the treadmill we asked participants to conduct three different tasks, which were counterbalanced across participants, for one minute each; First, walk freely with a straight forward viewing direction (straight); Second, explore the environment (environment). This meant looking along two dimensions, up and down, left and right; Third, walking while focusing on the feet (feet).

Participants performed these tasks first without using a headset to provide a baseline measurement of the gait behavior. Next, participants wore the HMD and performed the previous described walking tasks in VR. After they experienced one VR condition, participants left the treadmill and answered the PQ and AttrakDiff questionnaire. This procedure was counterbalanced over all participants for the egocentric conditions. In the final trial the exocentric condition was experienced. To get habituated to the scenario participants could experience the virtual environment for one minute on the treadmill before the actual study was conducted. Gait analysis for each participant was performed on around 50 strides for each task of the individual conditions. An overview of the study procedure is provided in Figure 5.

4 Results

An analysis of differences was performed using factorial repeated-measures analysis of variance. For testing spherical violation Mauchly's spherical test was applied [39]. The Greenhouse–Geisser adjustment was used to correct for violations of sphericity [21]. To estimate effect size, we report generalized eta squared (η_G^2) [47]. A significance level of $\alpha = .05$ was determined for all analyses.

4.1 Gait Parameters

For the gait parameters, first, results regarding the influence of the medium VR (Medium) in comparison to gait in in vivo is presented. Therefore, the four egocentric and the exocentric user perspectives were collapsed for each participant (VR). To investigate the two different VR perspectives, human representation (HUM) was compared to the exocentric (EXO) perspective. Further, we analyzed gait difference for context, by comparing gait results of the environment without (HUM) and with visual cues (HUM + ENV). We also investigated the differences of the four egocentric VR conditions (NoVis, PTC, SIL and HUM).

4.1.1 Medium

An overview of the differences between gait variability of the in vivo and VR condition in relation to the three different walking tasks is illustrated in Figure 6. Results of the repeated-measures ANOVA in terms of the gait variability showed a significant main effect for stride length for task (down, straight, environment) $F_{(2,32)} = 5.911, p = .006, \eta_G^2 = .043$ and condition (in vivo, VR) $F_{(1,16)} = 57.047, p < .001, \eta_G^2 = .405$ as well as an interaction effect between task and condition of $F_{(2,32)} = 4.996, p = .024, \eta_G^2 = .029$. Step width revealed significant differences for task $F_{(2,32)} = 40.870, p < .001, \eta_G^2 = .152$ and condition $F_{(1,16)} = 67.376, p < .001, \eta_G^2 = .302$. Further, also the stride time showed significant difference for task $F_{(2,32)} = 5.382, p = .009, \eta_G^2 = .053$ and condition $F_{(1,16)} = 43.219, p < .001, \eta_G^2 = .411$.

In the VR condition the stride time $F_{(2,32)} = 4.833, p = .018, \eta_G^2 = .073$, length $F_{(2,32)} = 6.704, p = .004, \eta_G^2 = .082$ and step width $F_{(2,32)} = 23.476, p < .001, \eta_G^2 = .114$ showed significant main effects for the individual tasks. For stride length and time this resulted in a significant difference between the tasks down and environment with $p = .007$ and $p = .002$ respectively. In terms of step width significant differences could be observed between environment and straight ($p < .001$) as well as down ($p < .001$). For the in vivo condition only a main effect between the tasks could be observed for step width $F_{(2,32)} = 23.223, p < .001, \eta_G^2 = .239$. A post hoc pairwise comparison revealed significant differences between environment and down ($p < .001$) as well as straight ($p < .001$).

4.1.2 Perspective

The analysis of variance for the COV resulted in main significant effects for task (down, straight, environment) for all gait parameters. In detail, stride time showed a significant main effect for task of $F_{(2,32)} = 6.563, p = .004, \eta_G^2 = .124$. Further, for stride length a significant main effect for task with $F_{(2,32)} = 9.084, p = .001, \eta_G^2 = .120$ could be observed. Comparable, step width resulted in a significant main effect for task $F_{(2,32)} = 24.689, p < .001, \eta_G^2 = .137$. Figure 7 illustrates the results of the COV analysis.

For the HUM condition a main effect for task could be observed for step width and stride length with $F_{(2,32)} = 22.227, p < .001, \eta_G^2 = .158$ and $F_{(2,32)} = 6.021, p = .011, \eta_G^2 = .126$ respectively. For step width a significant difference between environment and down ($p < .001$) as well as between straight and environment ($p < .001$) could be observed. Stride length showed a significant difference between down and environment ($p = .015$).

The analysis of the tasks also showed a main effect in terms of the exocentric perspective for all variations of the three gait parameters. Therefore we could observe an effect of $F_{(2,32)} = 8.335, p = .003, \eta_G^2 = .201$ for stride time, $F_{(2,32)} = 6.154, p = .009, \eta_G^2 = .131$ for stride length, and $F_{(2,32)} = 10.614, p = .002, \eta_G^2 = .118$ for step width. Results of the post hoc test revealed a significant difference between environment and down ($p = .026$) and environment and straight ($p = .002$) for step width. For stride length and time a significant difference between environment and down with $p = .013$ and $p = .006$ could be observed respectively.

4.1.3 Context

For the context we compared the influence of additional environmental cues as depicted in Figure 3a (HUM) and 3b (HUM + ENV). Figure 8 illustrates the results of the COV regarding the different tasks for both conditions.

Results of the COV analysis revealed a significant main effect for condition (HUM, HUM + ENV) for stride time $F_{(1,16)} = 6.418, p = .036, \eta_G^2 = .133$. This was significantly different ($p = .043$) for stride time in terms of the down task.

For the condition with supportive visual cues (HUM + ENV), we could observe a significant main effect for task in terms of stride time and length as well as step width with $F_{(2,32)} = 5.617, p = .028, \eta_G^2 = .183$, $F_{(2,32)} = 5.847, p = .014, \eta_G^2 = .155$, and $F_{(2,32)} = 6.419, p = .019, \eta_G^2 = .079$ respectively. In terms of stride time ($p = .022$) and length ($p = .009$) this resulted in a significant difference between the task environment and down. For step width down ($p = .034$) and straight ($p < .001$) showed significant difference to environment.

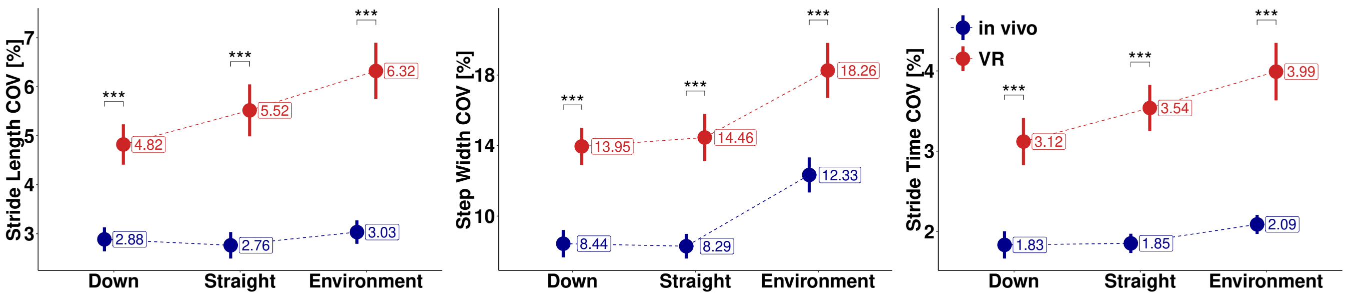


Figure 6: Mean and mean standard error (SEM) of the Coefficient of variation (COV) for the comparison of the stride length and time as well as step width of participants' natural gait and the gait in VR in relation to the three different walking tasks (down at the feet, looking straight to the front, and looking around the environment).

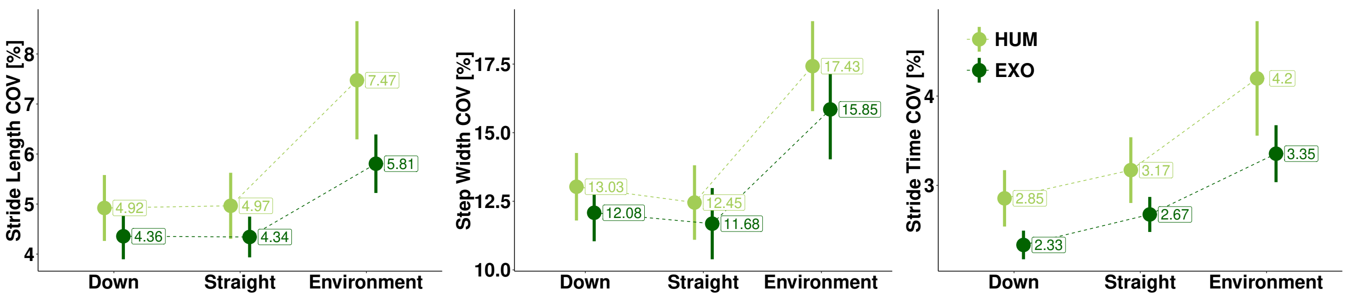


Figure 7: Mean and mean standard error (SEM) of the COV for the three different gait parameters stride length and time as well as step width regarding the exocentric and egocentric user perspectives differentiated by the three different walking tasks.

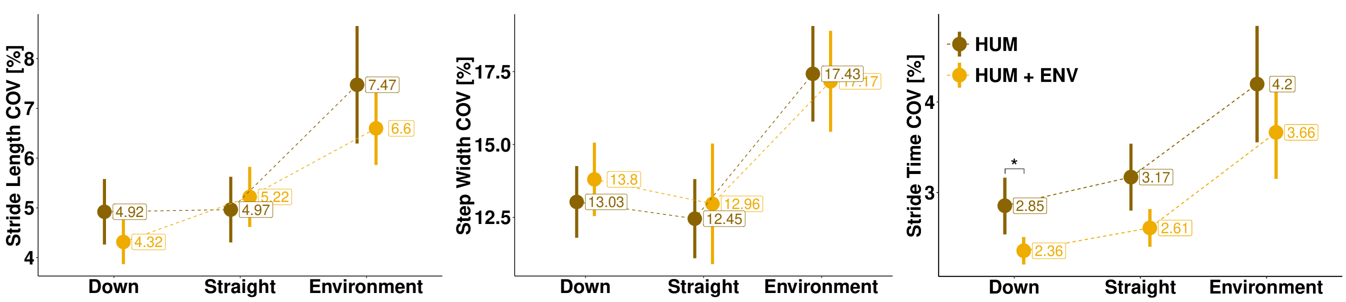


Figure 8: Mean and mean standard error (SEM) of COV for the three measured gait parameters stride length and time as well as step width regarding the environment with and without additional visual cues.

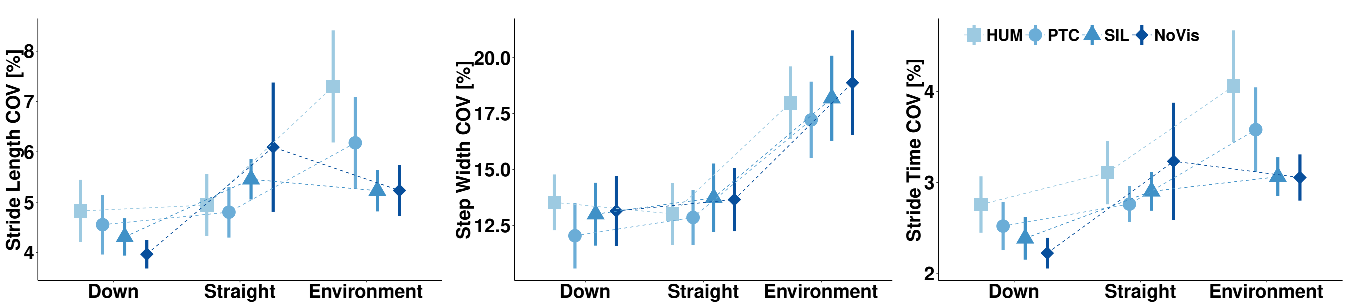


Figure 9: Participants' gait COV in terms of stride length and time as well as step width for the four egocentric avatar representations over the three different walking tasks. The illustrations depict the mean and mean standard error (SEM) of the individual conditions.

4.1.4 Avatar Appearance

For examination of avatar appearance we compared the four egocentric perspectives regarding their influence on participants' gait behavior (Fig. 9). The conducted analysis of variance showed a main effect for task in terms of stride time ($F_{(2,32)} = 10.092, p = .002, \eta_G^2 = .016$) and length ($F_{(2,32)} = 9.282, p = .003, \eta_G^2 = .005$) as well as step width ($F_{(2,32)} = 18.188, p < .001, \eta_G^2 = .025$). The pairwise post hoc analysis resulted in a significantly higher value for environment compared to down for stride time ($p < .001$) and length ($p < .001$). Comparable, the environment task showed a significant higher score compared to down ($p < .001$) and straight ($p < .001$) for step width.

4.2 User Experience

In terms of user experience the four different subcategories practical quality (PQ), hedonic quality of identification (HQ_I) and stimulation (HQ_S) as well as attractiveness (ATT) were examined.

4.2.1 Perspective

Results of the conducted paired-samples t-tests for the individual subcategories showed significant differences for ATT , HQ_I, and PQ in regard to the two perspectives (HUM, EXO). Table 1 shows that for all the individual subcategories of the user experience the exocentric condition was rated higher compared to its counterpart.

Table 1: UX results of the HUM and EXO condition.

Subcategory	HUM†	EXO †	p
ATT	5.06(±0.10)	5.55(±0.14)	.012
HQ_I	4.45(±0.07)	4.95(±0.15)	.003
HQ_S	4.83(±0.11)	4.82(±0.17)	.96
PQ	4.67(±0.06)	5.07(±0.14)	.024

Note. † *Mean (± standard error of the mean (SEM))*

4.2.2 Context

For the user experience in terms of the two different environments, we could observe no significant difference between the environment without and with visual cues for all subcategories of the AttakDiff questionnaire when conducting paired-samples t-tests. However, the environment with addition visual cues $M = 5.07$ ($SD = .76$) showed a higher overall score compared to its counterpart $M = 4.75$ ($SD = .74$).

4.2.3 Avatar Appearance

For the different user representations we found a significant main effect for the subcategories with $F_{(3,48)} = 3.345, p = .037, \eta_G^2 = .123$. The conducted post hoc analysis showed a significant differences for HQ_I ($p = .022$) between the HUM $M = 4.45$ ($SD = .70$), and NoViS $M = 3.76$ ($SD = .94$) condition. Further, a significant difference regarding this pair could also be observed for HQ_S ($p = .041$) with $M = 4.83$ ($SD = .75$) and $M = 4.24$ ($SD = .99$) respectively. For all subcategories HUM was rated highest and NoVis lowest.

4.3 Presence

To investigate the perceived presence of the participants we analyzed the subcategories realism, possibility to act (PossToAct), possibility to examine (PossExam), the quality of the interface (Interface), and the subjective perceived performance.

4.3.1 Perspective

Results of the conducted paired-samples t-tests for the subcategories revealed significant differences for the HUM and EXO perspective for realism, PossToAct and performance. As depicted in Table 2 the EXO condition showed higher ratings for all subcategories of presence.

Table 2: Presence results of the HUM and EXO condition.

Subscategory	HUM†	EXO†	p
$Interface$	5.78(±0.17)	6.10(±0.18)	.188
$Performance$	5.22(±0.22)	6.18(±0.19)	.002
$PossExam$	4.64(±0.22)	4.90(±0.17)	.391
$PossToAct$	5.28(±0.18)	5.90(±0.19)	.029
$Realism$	4.68(±0.15)	5.34(±0.24)	.033

Note. † *Mean (± standard error of the mean (SEM))*

4.3.2 Context

Regarding context the environment with additional visual cues outperformed the environment without reference for all subcategories of presence. The results of the conducted paired-samples t-tests showed a significant difference ($p = .011$) for PossToAct between HUM $M = 5.28$ ($SD = .75$) and HUM + ENV $M = 5.66$ ($SD = .41$).

4.3.3 Avatar Appearance

For user representation we could observe a significant main effect for condition $F_{(3,45)} = 10.320, p < .001, \eta_G^2 = .105$. The significant results of the pairwise post hoc test are depicted in Table 3.

Table 3: Presence results of the four egocentric user representations.

	Mean (± SD) 1	Mean (± SD) 2	p
$PTC - NoVis_{Realism}$	4.86(±.97)	3.30(±1.07)	< .001
$SIL - NoVis_{Realism}$	5.23(±.72)	3.30(±1.07)	< .001
$HUM - NoVis_{Realism}$	4.68(±.67)	3.30(±1.07)	< .001
$PTC - NoVis_{PossToAct}$	5.69(±.98)	4.29(±1.03)	< .001
$SIL - NoVis_{PossToAct}$	5.52(±.78)	4.29(±1.03)	.002
$HUM - NoVis_{PossToAct}$	5.28(±.75)	4.29(±1.03)	.011

5 Discussion

5.1 Medium

The results of this work demonstrate significant differences in gait of participants when comparing in vivo and VR, which is in line with, and extends, previous work [6, 15, 26]. This affects gait variability regarding stride length and time as well as step width. A higher variation in stride length and time as well as step width seems to indicate a higher gait insecurity of the participants [25]. Comparable results could be observed in a study conducted by Hollman et al., introduced in the related work. Results of the study indicate a variation in gait stability in terms of VR and non-VR walking when using a hemispherical display [28]. Within this work, we could show that this also applies when using a HMD that fully immerses participants into VR using avatar representations.

Another key finding is the difference of gait variability in relation to the three walking tasks. For the in vivo condition we could only observe a significant change for step width. Thereby, a greater instability occurred when participants explored the environment. This shows that the applied exploration task is more demanding for the participants and hence changes the gait behavior. An experiment conducted by Ebersbach et al. could reveal that simple motor tasks during walking result in a change of particpants' gait behavior [10].

Interestingly, we observed a difference in variation of stride length and time while participants were focusing on their feet compared to the exploratory task, but not between exploration and looking straight for the VR condition. The reason for this could be that the limitation in vertical field of view (FOV) of the HMD reduces important peripheral information (i.e. feet) and therefore provokes more instability for natural walking behavior.

Consequently, our results could not only show differences in variability of gait between in vivo and VR, but also give valuable insights that additional motor tasks effect gait stability differently in VR compared to in vivo. This is decisive when it comes to the domain of medical diagnosis and treatment. For example in the field of neurodegenerative diseases, where gait behavior is used to analyze the progression of the diseases, being aware of the influence of immersive media is important to avoid malpractice [16, 18]. Further, our findings are relevant for application areas where locomotion ability skills gained based on VR training need to be transferred to regular overground walking like in stroke injury treatment [17, 41]. Whereas in this case most literature investigates the effect of treatment based on VR, they lack to consider possible impacting characteristics of the environment and the applied task design on the efficiency of the intervention.

5.2 Perspective

We further explored the influence of an ego- and exocentric perspective on gait within our study. Results could show that overall gait variability was lower for the exocentric condition. Even though not significant, the tendencies that can be observed for the mean and variability could prove to be in an increased sample size. Based on the first results of this study this should be further addressed in future research. One limitation of this work is that the exocentric perspective was always experienced last by the participants. This was standardized in the conducted experimental block due to practical procedure considerations. Therefore further research should investigate order effects.

Comparable to the gait results, the presence and user experience for the exocentric perspective was rated higher. This includes the subjective evaluated performance and perceived realism of the participants. Hence, participants seemed not to favor a perspective in VR that is common to real-life (egocentric) during the experiment. One reason for this might be that since participants did not have major experience with VR environments, an omnipresent reference object within their center FOV (exocentric avatar) might have been beneficial for them to adapt to the new situation. This statement is supported by work of Salamin et al. exploring the benefits of different perspectives in VR related to a variety of tasks. They argue that while an exocentric perspective is preferable for displacement actions, an egocentric one is beneficial when looking down or in front of us [56, 57]. Another related reason could be that the relatively small FOV of the used HMD has a larger negative impact on the overview of the situation in an egocentric perspective.

5.3 Context

In the conducted study we also investigated the influence of additional visual cues within the VE on gait variability. These cues did not provoke any significant differences except for the looking-at-the-feet task for variation of stride time. Further, for the different tasks, only the exploration one seems to negatively influence gait variability compared to the others for both conditions. Even though not significant, when looking at the variation of stride time, we could observe an overall reduced gait variability while including additional environmental cues. One reason why we could only observe a low effect could be that within our study these cues were rather unobtrusive and may only mildly have affected the participants' perception.

The subjective measures strengthen this statement, since no essential differences for user experience and presence of participants could be observed for the two explored environments. In an experiment conducted by Graci et al. they could observe effects of participants' gait, while occluding parts of the peripheral visual field during real-life walking tasks. Their results show, that these occlusions lead to a negative effect in gait behavior [19]. Even though we could not observe statistically significant changes by using additional visual cues, the results do show a seemingly clear difference that might result in significant observations if the study population is increased.

5.4 Avatar Appearance

When looking at the gait variability in terms of the individual egocentric avatar appearances, we could not find significant differences. In line with this, participants did also not perceive differences in the subjective rated performance for the different user perspectives. However, they experienced the degree of realism and the possibility to act to be different. For these categories the missing self-representation (NoVis) was rated significantly lower compared to all other conditions. This indicates that even though participants may have a different perception of presence for individual avatar representations in VR, this seems to not mainly influence their performance. Consequently, for simple walking tasks in VR, it seems not to be decisive what type of egocentric self-representation is given to the user. Nevertheless, this result has to be interpreted with caution, since in our study we only examined tasks distinguishing in the visual focus of the user. To holistically understand the impact of user representations on gait in VR, more complex motor tasks should be evaluated in future studies. Further, it should be considered that we evaluated gait variability of participants that did not have any type of physical impairments. Since clinical VR based gait analysis and training is mainly used for patients that show some kind of physical impairment, it would be of interest for future research if comparable effects can be observed for this target group.

6 Conclusion and Future Work

In this work, we designed a VR system that enables full body motion captured avatar mapping on a treadmill to simulate different walking tasks in a VE. It was used to evaluate the impact of VR as a medium in combination with three simple walking tasks on gait variability. Furthermore, different user representations and perspectives were examined regarding their influence on the participants' gait behavior. The impact of visual cues on gait was also investigated by examining two different environmental representations.

Results show that natural gait of participants was significantly different to the respective gait characteristics in VR. We could also show, that the effect of simple motor tasks while walking influences gait stability differently in VR compared to in vivo. Further, differences in presence of users could be observed for different user perspectives. For environmental aspects, we could observe a tendency that peripheral visual cues can have a positive effect on gait variability in VR. Regarding the individual egocentric avatar appearances, no differences in gait behavior could be found. Our results suggest that when conducting gait assessment or training in VR, it is decisive to know that the medium itself, and thus its virtual internal visualizations, influences gait characteristics. This is especially relevant in clinical applications, where gait parameters may be regarded as disease specific markers. Our results further suggest that particular care has to be taken when comparing gait data or results from subjects immersed in VR and that equivalence of characteristics with in vivo may not be blindly assumed.

Acknowledgments

Bjoern Eskofier gratefully acknowledges the support of the German Research Foundation (DFG) within the framework of the Heisenberg professorship programme (grant number ES 434/8-1).

REFERENCES

[1] A. D. Andrade, J. G. Ruiz, M. J. Mintzer, P. Cifuentes, R. Anam, J. Diem, O. W. Gomez-Marin, H. Sun, and B. A. Roos. Medical students' attitudes toward obese patient avatars of different skin color. In *Medicine Meets Virtual Reality 19: NextMed, MMVR 2012*, pp. 23–29, 2012.

[2] S. Badarny, J. Aharon-Peretz, Z. Susel, G. Habib, and Y. Baram. Virtual reality feedback cues for improvement of gait in patients with parkinson's disease. *Tremor and Other Hyperkinetic Movements*, 4, 2014.

[3] D. Banakou, R. Groten, and M. Slater. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences*, 110(31):12846–12851, 2013.

[4] J. Blascovich, J. Loomis, A. C. Beall, K. R. Swinth, C. L. Hoyt, and J. N. Bailenson. Immersive virtual environment technology as a methodological tool for social psychology. *Psychological Inquiry*, 13(2):103–124, 2002.

[5] B. Bodenheimer and Q. Fu. The effect of avatar model in stepping off a ledge in an immersive virtual environment. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*, pp. 115–118, 2015.

[6] A. Canessa, P. Casu, F. Solari, and M. Chessa. Comparing real walking in immersive virtual reality and in physical world using gait analysis. In *VISIGRAPP (2: HUCAPP)*, pp. 121–128, 2019.

[7] Y. Choi, J. Lee, and S.-H. Lee. Effects of locomotion style and body visibility of a telepresence avatar. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1–9. IEEE, 2020.

[8] I. J. De Rooij, I. G. Van De Port, and J.-W. G. Meijer. Effect of virtual reality training on balance and gait ability in patients with stroke: systematic review and meta-analysis. *Physical therapy*, 96(12):1905–1918, 2016.

[9] S. Del Din, B. Galna, A. Godfrey, E. M. Bekkers, E. Pelosin, F. Nieuwhof, A. Mirelman, J. M. Hausdorff, and L. Rochester. Analysis of free-living gait in older adults with and without parkinson's disease and with and without a history of falls: identifying generic and disease-specific characteristics. *The Journals of Gerontology: Series A*, 74(4):500–506, 2017.

[10] G. Ebersbach, M. R. Dimitrijevic, and W. Poewe. Influence of concurrent tasks on gait: a dual-task approach. *Perceptual and motor skills*, 81(1):107–113, 1995.

[11] S. Edd, N. V. Martins, S. Bennour, B. Ulrich, B. Jolles, and J. Favre. Changes in lower limb biomechanics when following floor-projected foot placement visual cues for gait rehabilitation. *Gait & Posture*, 77:293–299, 2020.

[12] N. Epley, A. Waytz, and J. T. Cacioppo. On seeing human: a three-factor theory of anthropomorphism. *Psychological review*, 114(4):864, 2007.

[13] B. M. Eskofier, S. I. Lee, M. Baron, A. Simon, C. F. Martindale, H. Gassner, and J. Klucken. An overview of smart shoes in the internet of health things: Gait and mobility assessment in health promotion and disease monitoring. *Applied Sciences*, 7:986, 2017.

[14] T. Feigl, L. Gruner, C. Mutschler, and D. Roth. Real-time gait reconstruction for virtual reality using a single sensor. In *2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pp. 84–89, 2020. doi: 10.1109/ISMAR-Adjunct51615.2020.00037

[15] T. Feigl, D. Roth, S. Gradl, M. Wirth, M. E. Latoschik, B. M. Eskofier, M. Philippsen, and C. Mutschler. Sick moves! motion parameters as indicators of simulator sickness. *IEEE Transactions on Visualization and Computer Graphics*, 25(11):3146–3157, 2019. doi: 10.1109/TVCG.2019.2932224

[16] D. Fitzgerald, J. Foody, D. Kelly, T. Ward, C. Markham, J. McDonald, and B. Caulfield. Development of a wearable motion capture suit and virtual reality biofeedback system for the instruction and analysis of sports rehabilitation exercises. In *2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 4870–4874. IEEE, 2007.

[17] J. Fung, C. L. Richards, F. Malouin, B. J. McFadyen, and A. Lamontagne. A treadmill and motion coupled virtual reality system for gait training post-stroke. *CyberPsychology & behavior*, 9(2):157–162, 2006.

[18] A. Gokeler, M. Bisschop, G. D. Myer, A. Benjaminse, P. U. Dijkstra, H. G. van Keeken, J. J. van Raay, J. G. Burgerhof, and E. Otten. Immersive virtual reality improves movement patterns in patients after acl reconstruction: implications for enhanced criteria-based return-to-sport rehabilitation. *Knee Surgery, Sports Traumatology, Arthroscopy*, 24(7):2280–2286, 2016.

[19] V. Graci, D. B. Elliott, and J. G. Buckley. Peripheral visual cues affect minimum-foot-clearance during overground locomotion. *Gait & posture*, 30(3):370–374, 2009.

[20] S. Gradl, M. Wirth, N. Machtlinger, R. Poguntke, A. Wonner, N. Rohleder, and B. M. Eskofier. The Stroop Room: A Virtual Reality-Enhanced Stroop Test. In *VRST '19: 25th ACM Symposium on Virtual Reality Software and Technology*, pp. 28:1–12. ACM Press, 2019.

[21] S. W. Greenhouse and S. Geisser. On methods in the analysis of profile data. *Psychometrika*, 24(2):95–112, 1959.

[22] N. Hamzeheinejad, D. Roth, J. Breuer, A. Rodenberg, and M. E. Latoschik. The Impact of Implicit and Explicit Feedback on Performance andExperience during VR-Supported Motor Rehabilitation. In *IEEE Conference on Virtual Reality and 3D User Interfaces Virtual Reality (VR), 2021*, 2021.

[23] N. Hamzeheinejad, D. Roth, D. Götz, F. Weilbach, and M. E. Latoschik. Physiological effectivity and user experience of immersive gait rehabilitation. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1421–1429. IEEE, 2019.

[24] M. Hassenzahl. Hedonic, emotional, and experiential perspectives on product quality. In *Encyclopedia of human computer interaction*, pp. 266–272. IGI Global, 2006.

[25] J. M. Hausdorff. Gait variability: methods, modeling and meaning. *Journal of neuroengineering and rehabilitation*, 2(1):1–9, 2005.

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

[27] J. H. Hollman, R. H. Brey, R. A. Robb, T. J. Bang, and K. R. Kaufman. Spatiotemporal gait deviations in a virtual reality environment. *Gait & posture*, 23(4):441–444, 2006.

[28] J. H. Hollman, M. K. Watkins, A. C. Imhoff, C. E. Braun, K. A. Akervik, and D. K. Ness. A comparison of variability in spatiotemporal gait parameters between treadmill and overground walking conditions. *Gait & posture*, 43:204–209, 2016.

[29] O. Janeh, O. Fründt, B. Schönwald, A. Gulberti, C. Buhmann, C. Gerloff, F. Steinicke, and M. Pötter-Nerger. Gait training in virtual reality: Short-term effects of different virtual manipulation techniques in parkinson's disease. *Cells*, 8(5):419, 2019.

[30] O. Janeh, N. Katzakis, J. Tong, and F. Steinicke. Infinity walk in vr: Effects of cognitive load on velocity during continuous long-distance walking. In *ACM Symposium on Applied Perception 2019*, pp. 1–9, 2019.

[31] O. Janeh, E. Langbehn, F. Steinicke, G. Bruder, A. Gulberti, and M. Poetter-Nerger. Walking in virtual reality: Effects of manipulated visual self-motion on walking biomechanics. *ACM Transactions on Applied Perception (TAP)*, 14(2):1–15, 2017.

[32] K. Kilteni, I. Bergstrom, and M. Slater. Drumming in immersive virtual reality: the body shapes the way we play. *IEEE transactions on visualization and computer graphics*, 19(4):597–605, 2013.

[33] J. Klucken, J. Barth, P. Kugler, J. Schlachetzki, T. Henze, F. Marxreiter, Z. Kohl, R. Steidl, J. Hornegger, B. Eskofier, et al. Unbiased and mobile gait analysis detects motor impairment in parkinson's disease. *PloS one*, 8(2):e56956, 2013.

[34] U. Lab. Revised presence questionnaire. 2004. https://docplayer.net/52991659-Presence-questionnaire-witmer-singer-vs-3-0-nov-1994-revised-by-the-uqo-cyberpsychology-lab-2004.html, [Online; accessed 01-February-2021].

[35] J.-E. R. Lee, C. I. Nass, and J. N. Bailenson. Does the mask govern the mind?: Effects of arbitrary gender representation on quantitative task performance in avatar-represented virtual groups. *Cyberpsychology, Behavior, and Social Networking*, 17(4):248–254, 2014.

[36] J.-L. Lugrin, J. Latt, and M. E. Latoschik. Anthropomorphism and

illusion of virtual body ownership. In *ICAT-EGVE*, pp. 1–8, 2015.

[37] J.-L. Lugrin, I. Polyschev, D. Roth, and M. E. Latoschik. Avatar anthropomorphism and acrophobia. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, VRST '16, p. 315–316. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2993369.2996313

[38] F. Marxreiter, H. Gaßner, O. Borozdina, J. Barth, Z. Kohl, J. C. Schlachetzki, C. Thun-Hohenstein, D. Volc, B. M. Eskofier, J. Winkler, et al. Sensor-based gait analysis of individualized improvement during apomorphine titration in parkinson's disease. *Journal of neurology*, 265(11):2656–2665, 2018.

[39] J. W. Mauchly. Significance test for sphericity of a normal n-variate distribution. *The Annals of Mathematical Statistics*, 11(2):204–209, 1940.

[40] A. Mirelman, I. Maidan, T. Herman, J. E. Deutsch, N. Giladi, and J. M. Hausdorff. Virtual reality for gait training: can it induce motor learning to enhance complex walking and reduce fall risk in patients with parkinson's disease? *The Journals of Gerontology: Series A*, 66(2):234–240, 2011.

[41] A. Mirelman, B. L. Patritti, P. Bonato, and J. E. Deutsch. Effects of virtual reality training on gait biomechanics of individuals post-stroke. *Gait & posture*, 31(4):433–437, 2010.

[42] B. J. Mohler, W. B. Thompson, S. H. Creem-Regehr, H. L. Pick, and W. H. Warren. Visual flow influences gait transition speed and preferred walking speed. *Experimental brain research*, 181(2):221–228, 2007.

[43] M. C. Moreira, A. M. de Amorim Lima, K. M. Ferraz, and M. A. Benedetti Rodrigues. Use of virtual reality in gait recovery among post stroke patients–a systematic literature review. *Disability and Rehabilitation: Assistive Technology*, 8(5):357–362, 2013.

[44] D. Munari, C. Fonte, V. Varalta, E. Battistuzzi, S. Cassini, A. P. Montagnoli, M. Gandolfi, A. Modenese, M. Filippetti, N. Smania, et al. Effects of robot-assisted gait training combined with virtual reality on motor and cognitive functions in patients with multiple sclerosis: A pilot, single-blind, randomized controlled trial. *Restorative Neurology and Neuroscience*, (Preprint):1–14, 2020.

[45] N. Ogawa, T. Narumi, and M. Hirose. Effect of avatar appearance on detection thresholds for remapped hand movements. *IEEE Transactions on Visualization and Computer Graphics*, 2020.

[46] N. Ogawa, T. Narumi, H. Kuzuoka, and M. Hirose. Do you feel like passing through walls?: Effect of self-avatar appearance on facilitating realistic behavior in virtual environments. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2020.

[47] S. Olejnik and J. Algina. Generalized eta and omega squared statistics: measures of effect size for some common research designs. *Psychological methods*, 8(4):434, 2003.

[48] T. C. Peck, S. Seinfeld, S. M. Aglioti, and M. Slater. Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and cognition*, 22(3):779–787, 2013.

[49] J. Perry, J. R. Davids, et al. Gait analysis: normal and pathological function. *Journal of Pediatric Orthopaedics*, 12(6):815, 1992.

[50] A. Peruzzi, I. R. Zarbo, A. Cereatti, U. Della Croce, and A. Mirelman. An innovative training program based on virtual reality and treadmill: effects on gait of persons with multiple sclerosis. *Disability and rehabilitation*, 39(15):1557–1563, 2017.

[51] C. Prakash, R. Kumar, and N. Mittal. Recent developments in human gait research: parameters, approaches, applications, machine learning techniques, datasets and challenges. *Artificial Intelligence Review*, 49(1):1–40, 2018.

[52] R. Reinhard, K. G. Shah, C. A. Faust-Christmann, and T. Lachmann. Acting your avatar's age: effects of virtual reality avatar embodiment on real life walking speed. *Media Psychology*, 23(2):293–315, 2020.

[53] W. Richard, L. Murphy IV, C. Marquardt Jr, and M. Braun. Measuring walking: a handbook of clinical gait analysis. 2013.

[54] D. Roth and M. Latoschik. Construction of the virtual embodiment questionnaire (veq). *IEEE Transactions on Visualization Computer Graphics*, 26(12):3546–3556, 2020. doi: 10.1109/TVCG.2020.3023603

[55] D. Roth, J.-L. Lugrin, M. E. Latoschik, and S. Huber. Alpha ivbo-construction of a scale to measure the illusion of virtual body ownership. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pp. 2875–2883, 2017.

[56] P. Salamin, T. Tadi, O. Blanke, F. Vexo, and D. Thalmann. Quantifying effects of exposure to the third and first-person perspectives in virtual-reality-based training. *IEEE Transactions on Learning Technologies*, 3(3):272–276, 2010.

[57] P. Salamin, D. Thalmann, and F. Vexo. The benefits of third-person perspective in virtual and augmented reality? In *Proceedings of the ACM symposium on Virtual reality software and technology*, pp. 27–30. ACM, 2006.

[58] V. Schwind, P. Knierim, C. Tasci, P. Franczak, N. Haas, and N. Henze. " these are not my hands!" effect of gender on the perception of avatar hands in virtual reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 1577–1582, 2017.

[59] S. Shahnewaz, I. Afarat, T. I. Gayani, S. Mikael, D. Labbe, J. Quarles, et al. Gaitzilla: A game to study the effects of virtual embodiment in gait rehabilitation. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 265–266. IEEE, 2016.

[60] M. Slater, D. Pérez Marcos, H. Ehrsson, and M. V. Sanchez-Vives. Towards a digital body: the virtual arm illusion. *Frontiers in human neuroscience*, 2:6, 2008.

[61] H. Sveistrup. Motor rehabilitation using virtual reality. *Journal of neuroengineering and rehabilitation*, 1(1):10, 2004.

[62] S. van Sint Jan. *Color Atlas of Skeletal Landmark Definitions E-Book: Guidelines for Reproducible Manual and Virtual Palpations*. Elsevier Health Sciences, 2007.

[63] M. W. Whittle. Clinical gait analysis: A review. *Human movement science*, 15(3):369–387, 1996.

[64] M. Wirth, S. Gradl, W. A. Mehringer, R. Kulpa, H. Rupprecht, D. Poimann, A. F. Laudanski, and B. M. Eskofier. Assessing personality traits of team athletes in virtual reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 101–108. IEEE, 2020.

[65] M. Wirth, S. Gradl, D. Poimann, H. Schaefke, J. Matlok, H. Koerger, and B. M. Eskofier. Assessment of perceptual-cognitive abilities among athletes in virtual environments: Exploring interaction concepts for soccer players. In *Proceedings of the 2018 Designing Interactive Systems Conference*, pp. 1013–1023. ACM, 2018.

[66] B. G. Witmer and M. J. Singer. Measuring presence in virtual environments: A presence questionnaire. *Presence*, 7(3):225–240, 1998.

[67] T. A. Wren, G. E. Gorton III, S. Ounpuu, and C. A. Tucker. Efficacy of clinical gait analysis: A systematic review. *Gait & posture*, 34(2):149–153, 2011.

[68] N. Yee and J. Bailenson. The proteus effect: The effect of transformed self-representation on behavior. *Human communication research*, 33(3):271–290, 2007.