

Walking in Virtual Reality: Effects of Manipulated Visual Self-Motion on Walking Biomechanics

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Walking constitutes the predominant form of self-propelled movement from one geographic location to another in our real world. Likewise, walking in virtual environments (VEs) is an essential part of a users experience in many application domains requiring a high degree of interactivity. However, researchers and practitioners often observe that basic implementations of virtual walking, in which head-tracked movements are mapped isometrically to a VE are not estimated as entirely natural. Instead, users estimate a virtual walking velocity as more natural when it is slightly increased compared to the users physical body movement.

In this article, we investigate the effects of such nonisometric mappings between physical movements and virtual motions in the VE on walking velocity and biomechanics of the gait cycle. Therefore, we performed an experiment in which we measured and analyzed parameters of the biomechanics of walking under conditions with isometric as well as nonisometric mappings. Our results show significant differences in most gait parameters when walking in the VE in the isometric mapping condition compared to the corresponding parameters in the real world. For nonisometric mappings we found an increased divergence of gait parameters depending on the velocity of visual self-motion feedback. The results revealed a symmetrical effect of gait detriments for up- or down-scaled virtual velocities, which we discuss in the scope of the previous findings.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; • **Computing methodologies** → *Virtual reality*;

Additional Key Words and Phrases: Virtual environments, real walking, translation gains, biomechanics, gait

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1. INTRODUCTION

Bipedal walking is often considered the most basic and natural form of locomotion humans can perform. Thus, realizing real walking in virtual environments (VEs) is essential to support a veridical model of reality (i.e., as in the real world) in a wide range of application domains, such as virtual reality (VR) training, rehabilitation, simulation, or entertainment. To gain similar advantages from virtual walking as we gain from walking in the real world, such as navigation performance [Ruddle and Lessels 2009], spatial awareness [Ruddle and Péruch 2004], or presence [Usoh et al. 1999], it is important that virtual walking matches natural walking as close as possible. During walking in the real world, vestibular, proprioceptive, and efferent copy signals, as well as visual information create a consistent multi-sensory representation of a person's self-motion, that is, acceleration, speed, and walking direction. Modifying the sensory information during the movement can come from either proprioceptive information or efference copies of the motor command during the preparation for motor output [Pynn and DeSouza 2013]. Efference copies are those neural representations of motor outputs that predict reafferent sensory feedback and modulate the response of the corresponding sensory modalities (such as visual, auditory, and proprioception). Also, accessing a copy of the efferent command allows the brain to prepare for the consequences of an intended motion before it has occurred [Harris et al. 2002]. Discrepancies between visual feedback and the vestibular-proprioceptive system, such as those occurring while using walking-in-place [Usoh et al. 1999; Templeman et al. 1999], treadmills [Schwaiger et al. 2007; Bouguila et al. 2002], or VirtuSpheres [Marsh et al. 2013], have been hypothesized to cause detriments in walking performance [Steinicke et al. 2013].

Real walking can be implemented in VEs by mapping the tracked head movements of a user to changes of the virtual camera, thus generating self-motion feedback from the VE, e.g., by means of an *isometric mapping* (sometimes called a one-to-one mapping [Steinicke et al. 2008]). Then, a one-meter movement in the real world is mapped to a 1-meter motion of the virtual camera in the corresponding direction in the VE.

However, while easy to implement, previous experiments found that such isometric mappings are often not estimated as entirely natural by users. Steinicke et al. [2008] introduced *translation gains*, sometimes referred to as velocity gains, to describe the ratio between a virtual translation and the corresponding translation of a user in the real world. Translation gains $g_t \in \mathbb{R}$ provide a way to formalize *nonisometric mappings*, in which a translation T in the real world can be mapped to a scaled translation $g_t \cdot T$ in the VE.

In a psychophysical experiment using a two-alternative forced-choice task, they analyzed at which point of subjective equality users estimated virtual translations to match their physical movements. They found that virtual translations had to be slightly increased by 7% over a user's physical movement in order for researchers to estimate them as equal [Steinicke et al. 2010]. Other studies reported similar requirements to up-scale virtual walking velocities over physical movements, although they differed in magnitude, such as up-scaling by 53% [Banton et al. 2005] or by 36% [Durgin et al. 2005]. Most researchers tried to explain these effects with limitations of the current VR hardware technologies or the subjective state of the users, who often walk more slowly and carefully in VEs than they would in the real world, e.g., due to fear of colliding with unseen walls.

However, while users might estimate a slightly increased virtual walking velocity as more natural, in general, we have to consider that these results from perceptual matching tasks and self-adjustments do not necessarily lead to changes in the biomechanics of walking, but more closely match those of walking in the real world. Thus, it might be detrimental for practical applications of real walking user interfaces. Unfortunately, so far, the existing body of literature does not provide a consistent

understanding of the effects of such isometric or nonisometric walking conditions on gait detriments in VEs [Mohler et al. 2007a; Multon and Olivier 2013; Steinicke et al. 2013].

In this article, we present an experiment in which we investigate the effects of isometric and non-isometric walking with a head-mounted display (HMD) on gait parameters. Our main contribution is:

—Analysis of biomechanical walking parameters indicating a closest match between virtual and real walking for an isometric mapping, while nonisometric mappings resulted in often symmetrically-shaped detriments both for up- and down-scaled virtual velocity.

This article is structured as follows: Section 2 gives an overview about previous work on virtual locomotion, biomechanics of walking, and self-motion perception in VEs. In Section 3, the experiment is described. Section 4 summarizes the results, which are discussed in Section 5. Section 6 concludes the article.

2. RELATED WORK

The study of locomotion and perception are the focus of many research groups analyzing walking in both real and virtual environments [Steinicke et al. 2013; Suma et al. 2012; Multon and Olivier 2013]. Since the perception of and interaction with virtual worlds may be influenced not only by visual information but also physiological information from the inner body senses, it is important to investigate contingencies that exist among the sensory and motor information that signal self-motion [Durgin et al. 2007] and differences between biomechanical parameters while walking in the real world versus within virtual spaces [Mohler et al. 2007a]. In particular, Mohler et al. [2007a] reported that walking parameters may affect a user's perception of virtual space. Differences in biomechanics of walking in virtual worlds have naturally been suggested as a potential factor contributing to the fact that distances in VEs are often overestimated or underestimated in comparison to the real world [Renner et al. 2013; Loomis and Knapp 2003; Interrante et al. 2006, 2008]. Furthermore, Riecke and Wiener [2007] found that users have larger difficulties orienting themselves in virtual worlds than in the real world, which might be affected by physiological movement signals and walking parameters as well.

Moreover, several studies investigated the potential to increase the naturalness of virtual walking velocities in VEs [Durgin and Kearns 2002; Durgin et al. 2004]. Banton et al. [2005] reported that the visually perceived velocity appears too slow compared to the physical walking velocity and presented experiments investigating the underestimation of visual flow velocities during treadmill walking. They reported that the visual flow velocity had to be increased by about 50% in a VE to appear normal. Notably, the perceived velocity of real walking is influenced by the application of virtual velocities, which produces a discrepancy between the real and virtual velocity [Steinicke et al. 2010]. Similarly, users tend to underestimate traveled distances in VEs [Frenz et al. 2007]. Experiments by Steinicke et al. [2010] showed that users estimate the virtual distance as smaller than the physically perceived distance against the applied velocity gains. A study performed by Durgin et al. [2004] suggested that discrimination of visual velocities near walking velocity is enhanced by the act of walking. Discrimination of slow visual velocities had a negative effect during walking, whereas discrimination of faster visual velocities was improved.

The analysis of the biomechanics of walking provides spatio-temporal parameters that examine global aspects of gait. A typical gait cycle is defined by a sequence of stance phase (when the foot remains in contact with the ground and comprising about 60% of the gait cycle) and swing phase (when the foot is not in contact with the ground and comprising about 40% of the gait cycle) [Multon and Olivier 2013]. Within a stance phase, the double support represents approximately 20%

[Alexander 2003; Inman et al. 1981], and single support represents approximately 40% of the gait cycle [Bogey 2014]. Therefore, when a foot is in a swing phase, the other foot should be in a single support phase. When a foot is in a stance phase, it goes through a double support phase, a single support phase, and another double support phase. In order to provide characteristics of the gait during walking, temporal and spatial parameters of gait have to be considered such as velocity, step length, step frequency, etc.

Many researchers [Durgin et al. 2007; Mohler et al. 2007b; Steinicke et al. 2013] have investigated physiological and biomechanical aspects of walking across different samples in an attempt to describe real and virtual environments while walking within a HMD and the real world. Mohler et al. [2007a] reported that gait parameters (such as velocity, stride length, head angle, etc.) within a VE are different than those in the real world. Furthermore, Sheik-Nainar and Kaber [2007] and Mohler et al. [2007b] found that visual information is associated with the control of locomotor behavior.

In particular, they found that gait velocity of self-motion is influenced by visual flow. Hollman et al. [2007] examined the effect of VEs on gait and found that walking in VEs increases variability in the ground reaction forces (such as weight acceptance peak and push-off peak) through a single footfall, which reflects compensatory efforts to control the body's center of mass over the base of support during locomotion and, therefore, represents gait instability induced by visual stimulation in VEs. However, the behavior of most people is different when walking in a VE than in the real world, whereas the question remains as to whether people walking within VEs show lower stability than during walking in the real world. We believe that it is important to investigate such aspects of human locomotion while walking in the real and virtual world.

3. EXPERIMENT

In this section, we present the experiment in which we have examined how walking in VEs differs from walking in the real world in terms of the biomechanics and velocity of walking. We tested different isometric and nonisometric walking conditions using the method of translation gains [Steinicke et al. 2010] along a straightforward movement path, and we compared the results to a baseline condition while walking in the real world. Prior to the experiment, we received approval for the experimental procedure, materials, and methods by our institutional review board.

3.1 Participants

A total of 19 participants (6 female and 13 male, ages 18-38, $M = 26.8$, heights 160-194cm, $M = 175.8$ cm, weights 52-87kg, $M = 69$ kg) completed the experiment. The participants were students or members of the Department of Computer Science or the Department of Neurophysiology. Students obtained class credit for their participation. All of our participants had normal or corrected-to-normal vision. During the experiment, six participants wore glasses and two participants wore contact lenses. None of our participants reported a disorder of equilibrium or vision disorders, such as color blindness or astigmatism. Participants wore an HMD for approximately 30 minutes during the experiment. Nine participants have had prior experience with HMDs before. We measured the leg length of our participants before the experiment (82–98cm, $M = 89.4$ cm). We used the leg length of each participant to calculate a functional ambulation performance (FAP) [Nelson 2008a], which represents a quantification of participants' gait based on a selection of spatio-temporal parameters obtained at a self-selected velocity [Gouelle et al. 2011; Gretz et al. 1998]. The selected parameters are standard velocity normalized to leg length, step and leg length ratio, step time, right-left asymmetry of step length, and dynamic base of support. Participants were naive to the experimental conditions, wearing their normal clothes and performing barefoot walking across a walkway. They were allowed to take breaks at any time between experiment trials in order to minimize effects of exhaustion or lack of concentration.

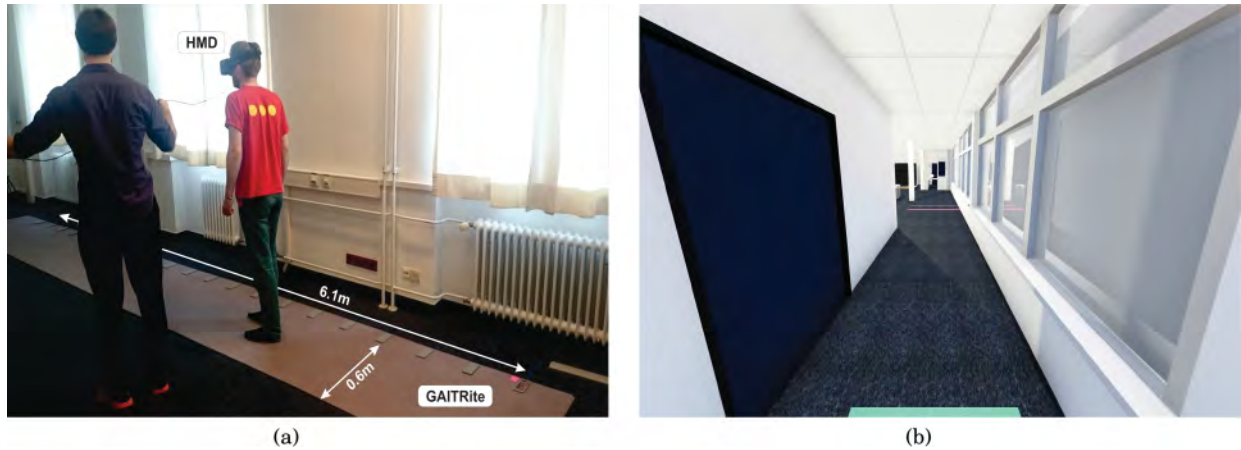


Fig. 1. Experiment setup: (a) A participant walks in the real workspace with an HMD over the GAITRite walking surface, and (b) the participant's view on the HMD.

The total time per participant, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing, was 1 hour.

3.2 Materials

We performed the experiment in a laboratory room of $9\text{m} \times 4\text{m}$ in size (see Figure 1). During the experiment, the room was darkened in order to reduce the participant's perception of the real world while immersed in the VE. The virtual space was rendered using Unity3D, a cross-platform game engine with a custom-enabled VR communications and rendering library. The visual stimulus was a 3D laboratory model. The start (green line) and target (red lines) were placed on the floor in front of the participant to indicate the walking distance in the virtual world. The participants have been instructed to walk from the start line to the target (i.e., stopping between the two target lines). In the VE, forward movement was accompanied by motion of the head-tracked without corresponding movements of the participant's self-representation. For rendering, system control, and logging, we used an Intel computer with 3.4GHz Core i7 processor, 16GB of main memory, and Nvidia GeForce 780Ti SLI graphics cards.

The participants wore an Oculus Rift DK2 HMD for the stimulus presentation, which provides a resolution of 960×1080 pixels per eye with a refresh rate of 60Hz and an approximate 110° diagonal field of view (FOV). We attached an active infrared marker to the HMD and tracked it using an optical tracking system (WorldViz precision position tracking PPT-X4) at an update rate of 60Hz with sub-millimeter precision and accuracy for position data in the laboratory. During the experiment, we provided comfort to the head from the weight of the cables by having an assistant manage the cables for each participant, making their presence transparent. In the real-world conditions without HMD, we attached an active infrared marker to a baseball cap that was worn on the head of each participant and tracked it using PPT.

While walking, temporal (timing) and spatial (2D geometric indicators of the participant's feet) gait parameters were measured using a GAITRite electronic walkway system [Nelson 2008b]. The electronic walkway system provides an active walking area of $0.6\text{m} \times 6.1\text{m}$ with a scanning frequency of 60Hz. The pressure exerted by the feet onto the walkway activated the sensors during walking. The sensors provided measurements using (x, y) coordinates with distance recorded in centimeters and time in seconds up to an accuracy of 6dp. The walking distance was 6m in all conditions.

3.3 Methods

Participants filled out an informed consent form and received detailed instructions on how to perform the walking tasks. Furthermore, they filled out the simulator sickness questionnaire (SSQ) [Kennedy et al. 1993] immediately before and after the experiment, consisting of 16 symptoms that are rated by the participant in terms of severity. These symptoms include, but are not limited to headache, nausea, burping, sweating, fatigue, and vertigo. Participants rated each symptom on a Likert-type scale [Likert 1932], including the options none, slight, moderate, and severe. Furthermore, the Slater-Usoh-Steed presence questionnaire (SUS PQ) [Slater 1999] was filled out after the experiment, as well as a demographics questionnaire.

We used a within-subjects design in which we tested eight walking conditions consisting of one real-world condition and seven translation gain conditions (cf. Section 1) while wearing the HMD. We tested translation gains in the following range: $g_t \in \{\frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1, \frac{5}{4}, \frac{3}{2}, \frac{7}{4}\}$, that is, visual flow presented at lower $g_t < 1$, matched $g_t = 1$, or higher speed $g_t > 1$. Each condition was repeated twice during the experiment. The order in which the conditions were tested was randomized. In total, each participant completed 16 trials.

The task was to first assume the start position by standing in orthostatic pose at the start line; the body is held in an upright position and supported only by the feet. Then, participants were instructed to walk in their normal pace along the walkway of the GAITRite system while coming to a halt between the location of the target lines (see Figure 1(a)). This was done with or without the HMD. After each trial, the participant had to walk back to the starting point.

3.4 Data Collection

Several spatio-temporal gait parameters are analyzed through the GAITRite walkway system. As illustrated in Figure 2, these parameters are:

- Walking velocity is the distance traveled by the body divided by the ambulation time. It is measured in centimeters per second (cm/sec).
- Step count is the number of steps taken while walking the 6m distance.
- Step length is the distance between corresponding successive placements of the opposite foot. The unit of measure is centimeters (cm).
- Base of support is the vertical distance from heel center of one footprint to the line of progression formed by two footprints of the opposite foot. The unit of measure is centimeters.
- FAP score is derived by subtracting points from a maximum score of 100 for walking at a self-selected velocity [Gretz et al. 1998]. A higher score is better in overall walking performance and is calculated according to the following equation:

$$FAPScore = 100 - (A + B + C), \quad (1)$$

where A denotes the dynamic base of support during ambulation, B is the degree of asymmetry of the participant's gait expressed as the ratio of the difference of the left and right step lengths divided by participant's leg length, and C denotes the relationship of step length/leg length ratios, step times, and velocities normalized for leg lengths.

- Toe in/out is the angle between the foot's line of progression and the mid line of the foot. The unit of measure is degrees (deg).
- Single support is the time elapsed between the last contact of the current footfall to the first contact of the next footfall of the same foot. It is measured in seconds (sec) and expressed as a percent of the gait cycle time, and is equivalent to the swing time.

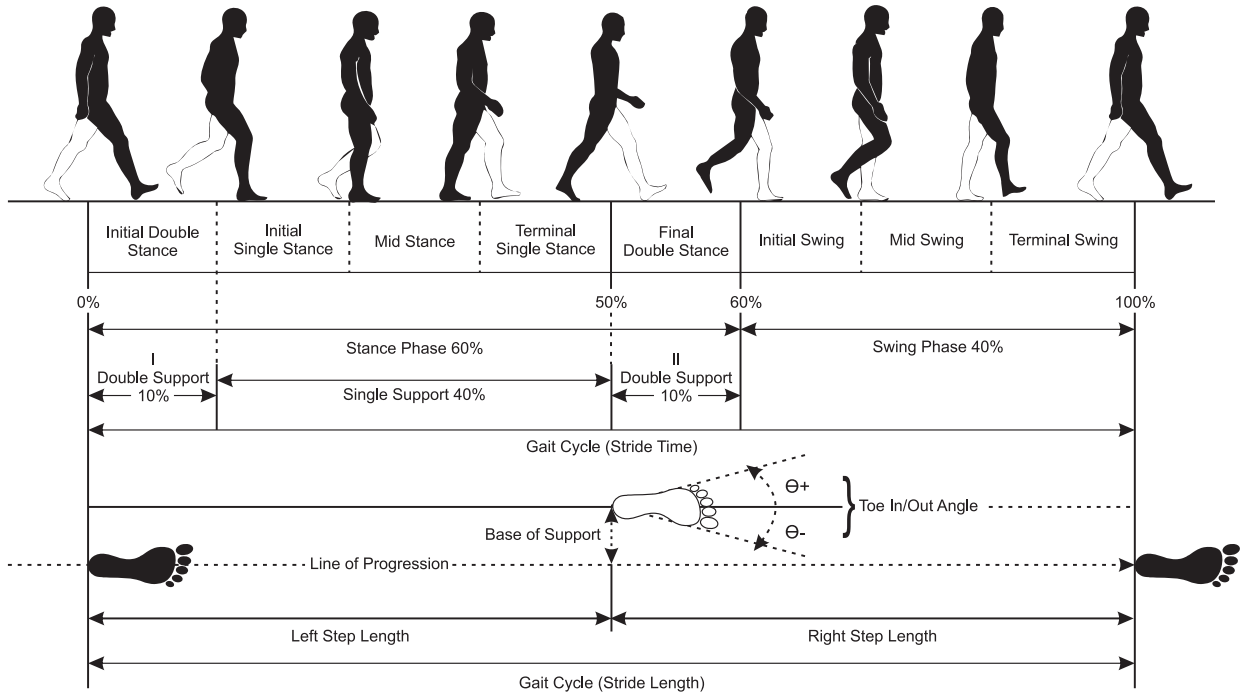


Fig. 2. Spatio-temporal gait parameters measured during the experiment.

—Double support is the amount of time that a participant spends with both feet on the ground during one gait cycle. It is measured in seconds and also expressed as a percent of the gait cycle time.

Furthermore, we collected data from the head-tracked HMD. In particular, head pitch angles were analyzed using the orientation data of the Oculus Rift DK2 HMD. While the yaw and roll angles of the participant’s head were expected to be near-constant due to the task of straightforward walking, we were interested in whether differences in gait would be accompanied by a tendency of the participants to pitch their head further down toward the floor. Such differences in pitch angles correspond to atypical head postures during walking, which indicate an additional difference from natural walking.

4. RESULTS

Figures 3 to 7 show the differences between the real and virtual walking conditions for the different dependent variables in the experiment. The x -axes show the translation gains g_t and the y -axes show the measured values pooled over the participants. The vertical bars show the standard error of the mean. We summarize the results of our experiment in the following sections (see also Table I):

4.1 Comparison Between Real and Virtual Walking

In order to compare the effects of the immersive and non-immersive walking conditions, we first considered only the data in the conditions while wearing the HMD in which the virtual walking velocity matched the real-world walking velocity, that is, with gains $g_t = 1$.

The results were normally distributed according to a Shapiro-Wilk test at the 5% level. We performed paired t-tests at the 5% significance level. We found a significant effect of immersion on walking velocity $t(18) = 3.26$, $p = .004$; step count $t(18) = -2.62$, $p = .018$; step length $t(18) = 3.83$, $p = .001$;

Table I. The Results of Statistical Analysis

	Paired sample t-tests		Repeated-measures ANOVAs with post-hoc tests			
	$t(18)$	p	g_t	F	p	η_p^2
Walking velocity	3.26	.004		(2.18, 39.16) = 3.35	.042	.157
			$g_t(1, 1.5)$.021	
			$g_t(1.25, 1.5)$.020	
Base of support	-2.14	.046		(4.52, 81.28) = 4.64	.001	.205
			$g_t(.25, 1.25)$.015	
			$g_t(.5, 1.25)$.041	
FAP score	3.63	.002		(2.35, 42.34) = 4.76	.010	.209
			$g_t(.25, .5)$.015	
			$g_t(1, 1.5)$		<.001	
			$g_t(1, 1.75)$.005	
Toe in/out	-3.96	.001		(3.28, 59.05) = 3.17	.027	.150
			$g_t(.5, 1.75)$.003	
			$g_t(1.25, 1.75)$.037	
Double support	-3.32	.004		(3.76, 67.61) = 3.61	.011	.167
			$g_t(.25, .5)$.055	
Step count	-2.62	.018		(2.37, 42.57) = 2.86	.060	.137
Step length	3.83	.001		(2.65, 47.63) = 2.20	.108	.109
Single support	.51	.620		(3.95, 71.02) = .508	.727	.027
Head pitch angle				(2.68, 48.22) = 37.27	<.001	.674
			$g_t(.25, .5, .75, 1, 1.25, 1.5, 1.75)$		<.050	

base of support $t(18) = -2.14$, $p = .046$; FAP score $t(18) = 3.63$, $p = .002$; toe in/out $t(18) = -3.96$, $p = .001$; and double support $t(18) = -3.32$, $p = .004$. We found no significant effect of immersion on single support $t(18) = .51$, $p = .620$. The results show that most gait parameters, while immersed with the HMD, differed from walking in the real world.

4.2 Comparison Between Translation Gains

We analyzed the results for the different translation gains in the immersive conditions with a repeated-measures ANOVA and Tukey multiple comparisons at the 5% significance level with Bonferroni correction. The results were normally distributed according to a Shapiro-Wilk test at the 5% level. Degrees of freedom were corrected using Greenhouse and Geisser [1959] estimates of sphericity in case Mauchly's test indicated that the assumption of sphericity had been violated [Mauchly 1940]. Partial eta squared (η_p^2) values provide an estimation of the effect size [Kennedy 1970; Cohen 1973]. The ranges of η_p^2 are between 0 and 1 (i.e., small $\sim .02$, medium $\sim .13$, and large $\sim .26$).

We found a significant main effect of translation gains on walking velocity, $F(2.18, 39.16) = 3.35$, $p = .042$, $\eta_p^2 = .157$; base of support, $F(4.52, 81.28) = 4.64$, $p = .001$, $\eta_p^2 = .205$; FAP score, $F(2.35, 42.34) = 4.76$, $p = .010$, $\eta_p^2 = .209$; toe in/out, $F(3.28, 59.05) = 3.17$, $p = .027$, $\eta_p^2 = .150$; double support, $F(3.76, 67.61) = 3.61$, $p = .011$, $\eta_p^2 = .167$; and head pitch angle, $F(2.68, 48.22) = 37.27$, $p < .001$, $\eta_p^2 = .674$.

Post-hoc tests showed significant differences for walking velocity only between translation gains $g_t = 1$ and $g_t = 1.5$ ($p = .021$), as well as between $g_t = 1.25$ and $g_t = 1.5$ ($p = .020$); for base of support only between translation gains $g_t = .25$ and $g_t = 1.25$ ($p = .015$), as well as between $g_t = .5$

and $g_t = 1.25$ ($p = .041$); for FAP score only between translation gains $g_t = .25$ and $g_t = .50$ ($p = .015$), between $g_t = 1$ and $g_t = 1.5$ ($p < .001$), between $g_t = 1$ and $g_t = 1.75$ ($p = .005$), as well as between $g_t = 1.25$ and $g_t = 1.5$ ($p = .004$); for toe in/out only between translation gains $g_t = .5$ and $g_t = 1.75$ ($p = .003$), as well as between $g_t = 1.25$ and $g_t = 1.75$ ($p = .037$). Post-hoc tests for double support showed no significant differences but a trend between translation gains $g_t = .25$ and $g_t = .5$ ($p = .055$). Post-hoc tests for head pitch angle showed significant differences between all translation gains (all $p < .05$).

We found no significant main effect but a trend of translation gains on step count, $F(2.37, 42.57) = 2.86$, $p = .06$, $\eta_p^2 = .137$. We also found no significant main effect of translation gains on step length, $F(2.65, 47.63) = 2.20$, $p = .108$, $\eta_p^2 = .109$, or on single support, $F(3.95, 71.02) = .508$, $p = .727$, $\eta_p^2 = .027$.

4.3 Questionnaires

We measured a mean SSQ score of $M = 9.2$ ($SD = 16.6$) before the experiment, and a mean SSQ score of $M = 10.2$ ($SD = 12.2$) after the experiment. The scores indicate overall low simulator sickness symptoms for walking with an HMD, and we found no significant increase of symptoms over the time of the experiment $t(18) = -.33$, $p = .745$. The mean SUS PQ score for the sense of feeling present in the VE was $M = 4.2$ ($SD = .58$), which indicates a high sense of presence [Slater 1999]. Additionally, participants judged their fear to collide with the walls of the room or other physical obstacles while immersed with the HMD during the experiment as comparably low (rating scale, 0=no fear, 4=high fear, $M = 1.1$, $SD = 1.3$).

5. DISCUSSION

Our results show that participants walked differently within the real and virtual environment in terms of nearly all tested gait parameters, and most gait differences increased when large discrepancies of virtual velocity were introduced with nonisometric mappings.

Walking Velocity. Concerning walking velocity, our results (shown in Figure 3 (a)) show a significant decrease of walking velocity by 6% while wearing the HMD compared to the real world, which is similar to results obtained in a study performed by Mohler et al. [2007a], who reported a decrease in walking velocity by 14%. Moreover, we found that walking velocity was further decreased the more translation gains differed from an isometric mapping with $g_t = 1$, which indicates an almost symmetrical effect of translation gains. This result is highly interesting since it is important to note that the effect of translation gains was actually different from what would be expected, based on a previous study with slightly different experimental design performed by Mohler et al. [2007b]. This study would have predicted that participants would increase their walking velocity when the virtual velocity was decreased with a gain $g_t < 1$, and not a decrease in walking velocity. Informal comments by our participants suggest that many of them felt that decreased virtual walking velocities lead to less stable walking along the path, thus inducing them to slow down even more. This result is also matched by the head pitch angles shown in Figure 7, which indicate that the participants looked down toward the floor when the virtual velocity was reduced, which may indicate that they received less visual flow information during walking, and thus had to orient more by the pathway shown on the floor.

FAP. Furthermore, as shown in Figure 3 (b), we found that the FAP score significantly decreased in the VE compared to the real world with respect to an isometric mapping with $g_t = 1$, which indicates that the number of points subtracted increased. Moreover, the FAP scores were reduced when nonisometric mappings were applied with translation gains $g_t \neq 1$, which indicates that selected parameters increasingly differed from normal gait. The points deducted in the different parts of the FAP score (see

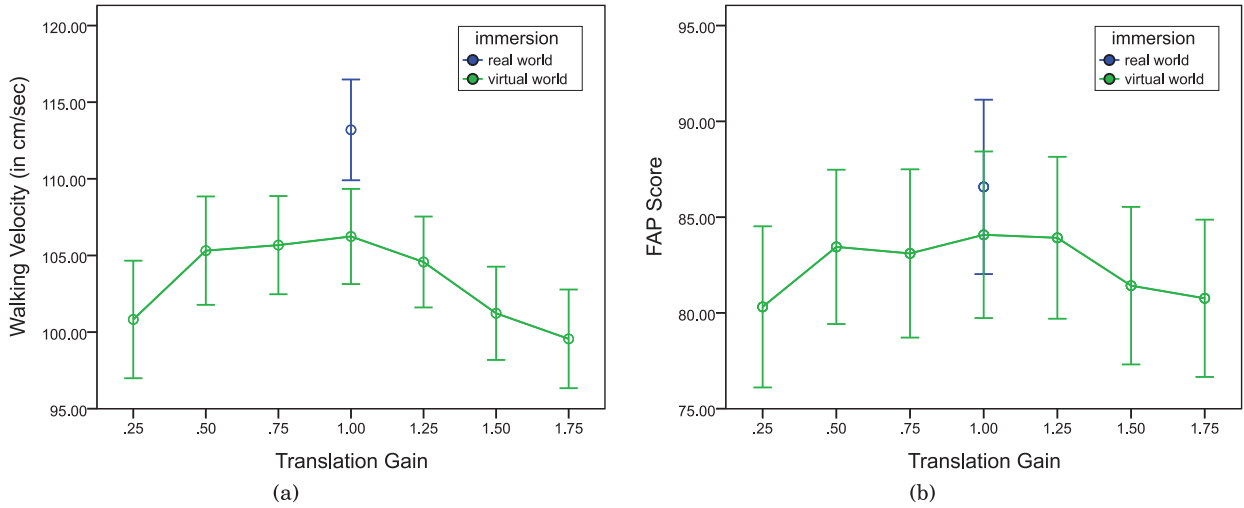


Fig. 3. Results for applied translation gains on the horizontal axis and pooled for (a) walking velocity and (b) FAP score on the vertical axis. The error bars show the standard error of the mean.

Equation (1) are determined by the distance between the participant's gait parameters and ranges of predefined values considered as normal for gait at the self-selected velocity [Gouelle 2014], for example, up to 8 points are deducted if the dynamic base of support is abnormally wide or narrow. Further points can be deducted from a maximum score of 100 (i.e., from 0 to 8 points for right-left asymmetry and from 0 to 22 points for right-left step functions). Regarding the deductible points intervening in FAP score calculation, we observed that a greater amount of points was deducted for dynamic base of support and asymmetry of step length. The deductions for functions of right and left steps were nonexistent or close of zero.

Step Length. Figure 4 shows that participants had a shorter step length in the VE than in the real world for $g_t = 1$. Moreover, the shortened step length in the VE positively correlated with an increase of the number of steps taken. These results also reflect a similar response to visual stimulation during the application of translation gains, regardless of whether translation gains $g_t < 1$ or $g_t > 1$ were applied. These results correlate with an instability of the participants' gait.

Base of Support. Figure 5 (a) shows the differences of base of support in the VE compared to the real world. The differences indicate that participants walked with a widened base of support in the VE for $g_t = 1$. A wide base of support has long been believed to be a hallmark of unsteady gait [Nutt et al. 1993]. This suggests that the participants tended to spread their feet apart, thereby increasing their bases of support while walking with an HMD in the VE. The base of support was wider with slower translation gains $g_t = .25$, and was narrower with faster translation gains $g_t = 1.75$. Thus, the effects of visual information at lower translation gains induced a wider base of support and would be more likely to increase stability in the VE. In this scope, we also found that the toe in/out (foot angle) in Figure 5 (b) increased, which indicates that participants walked with toes pointing further out within the VE. In contrast, we did not find any negative indicator of toe in/out within the VE or in the real world.

Double Support. Figure 6 shows a significantly prolonged double support period in the VE for $g_t = 1$, as well as a non-significant trend toward a shortened single support period. Also, the participants tended to prolong their double support period during the application of translation gains $g_t < 1$ and

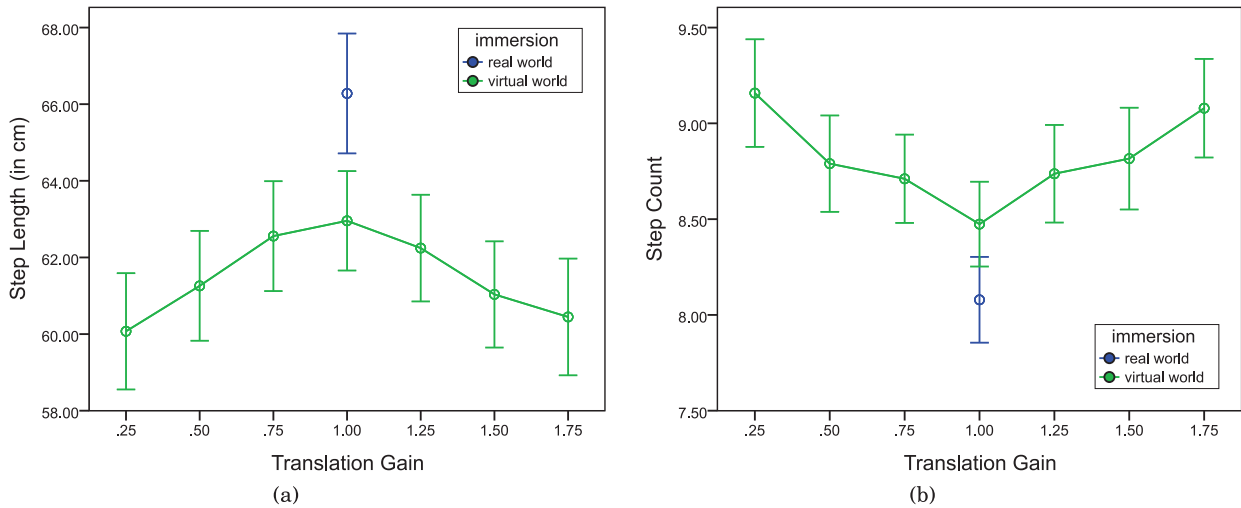


Fig. 4. Results for applied translation gains on the horizontal axis and pooled for (a) step count and (b) step length on the vertical axis. The error bars show the standard error of the mean.

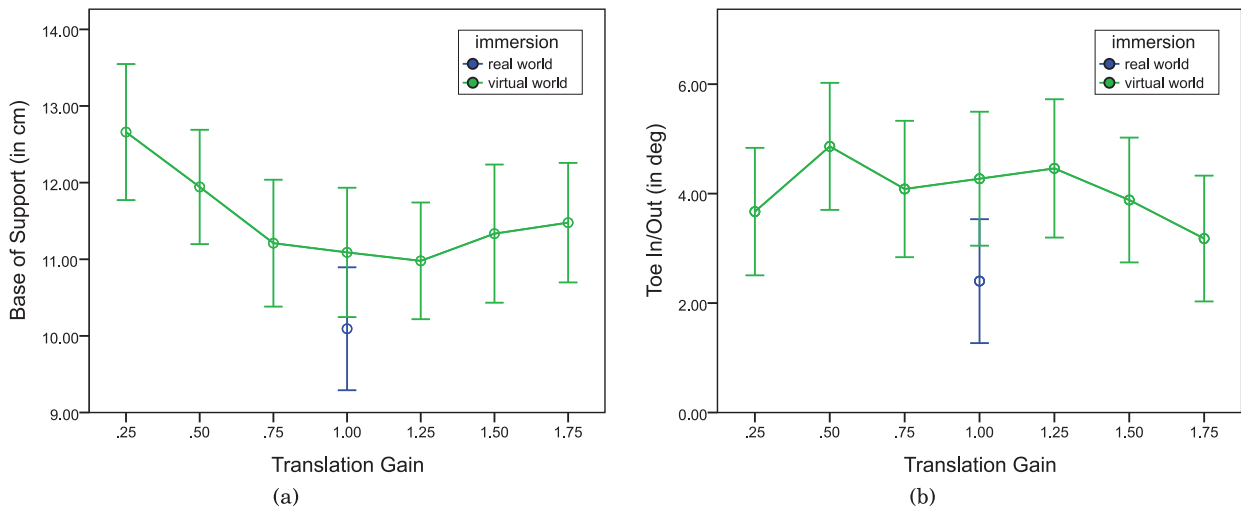


Fig. 5. Results for applied translation gains on the horizontal axis and pooled for (a) base of support and (b) toe in/out on the vertical axis. The error bars show the standard error of the mean.

$g_t > 1$, in which the body weight is supported by both legs. These findings indicate that the durations of stance phases are longer than swing phases throughout the virtual walking, which also justifies why the participants walked slower in the VE than in the real world.

Overall, most measured biomechanical parameters of gait were affected both by immersion and the application of translation gains during bipedal locomotion in the VE. The results underline the importance to investigate the differences between gait parameters while walking in the real world and within a VE. Specifically, our results show that virtual walking had much lower stability than walking in the real world, which might be explained by hardware factors such as the weight of the HMD, which causes a participant to walk differently in the VE [Willemsen et al. 2004]. In particular, Willemsen

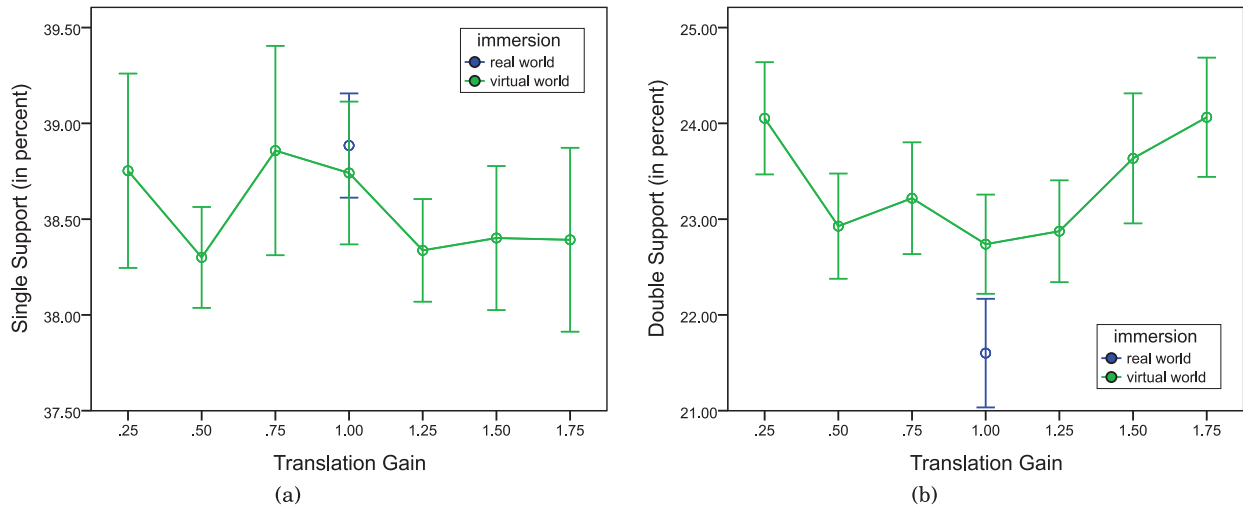


Fig. 6. Results for applied translation gains on the horizontal axis and pooled for (a) single support and (b) double support on the vertical axis. The error bars show the standard error of the mean.

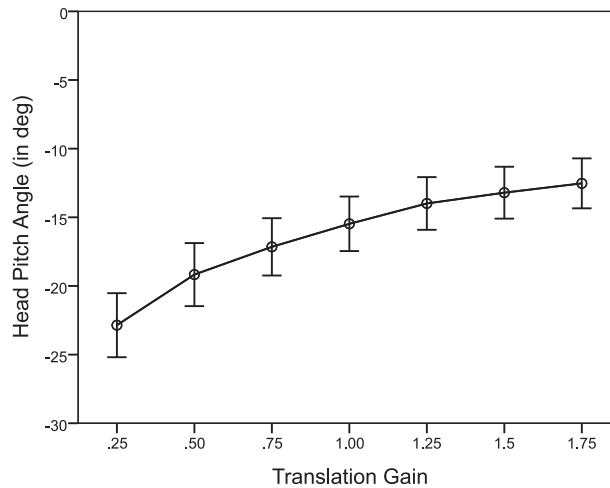


Fig. 7. Results for applied translation gains on the horizontal axis and pooled for head pitch angle on the vertical axis. The error bars show the standard error of the mean. A pitch angle of 0 indicates a level head, whereas negative angles indicate that the user was looking down toward the floor.

et al. [2004] have found evidence that issues related to the ergonomics of HMD systems may account for some of the apparent compression observed; an explanation for the larger portion of the effect remains wanting. Or, factors such as the availability of visual flow information when translation gains are applied while walking, e.g., visual flow, provide cues about the traveled distance. Within a VE, these cues are consistent and, hence, provide veridical information to the user about her motion. Although human subjects can use these cues to discriminate traveled distances [Frenz et al. 2007], it has been shown that perception in the virtual world varies significantly from perception in the real world.

Furthermore, walking in the VE was found to correlate with decreased walking velocity, decreased FAP score, decreased step length, increased step count, widening of the base of support, positive toe-out, shortened single support, and with prolonged double support. And, last but not least, we found that participants had a tendency to look down toward the floor when translation gains $g_t < 1$ were applied, but no such effect was visible for gains $g_t > 1$. These differences might be caused by the limited FOV of current HMDs. Jones et al. [2011] found evidence that a small FOV could produce improved distance judgments when real-world visual flow was added to the lower part of the periphery. However, the reason for this improvement remains unclear. A follow-up study by Jones et al. [2012] attempted to determine if the peripheral visual flow was causing observers to recalibrate their gait, enabling them to move more accurately in the VE. They found that gait did seem to be a partial contributing factor, but that it was insufficient to explain all the observed improvements. They speculated that the peripheral stimulation may have served as an additional reference to the location of the ground plane relative to the observer's eye position. Another potential explanation for the misinterpretation could be based on incorrect depth cues provided to the human eye when looking through an HMD, such as the accommodation convergence conflict [Hoffman et al. 2008]. Watt et al. [2005] stated that inappropriate depth cues in typical HMDs may therefore contribute to distortions in perceived space.

Considering that the previous literature indicated that users wearing an HMD subjectively estimate a slightly increased virtual walking velocity as more natural than walking using an isometric mapping, we have to say that this advantage of translation gains $g_t > 1$ is not visible in the gait parameters that we measured in this experiment. Conversely, independently of whether gains $g_t < 1$ or $g_t > 1$ were applied, we found that most parameters of the biomechanics of walking deviated from what is considered normal walking.

6. CONCLUSION

In this article, we have presented an experiment in which we evaluated the differences of biomechanical walking parameters between a real and virtual environment. In the virtual world conditions, we analyzed effects of nonisometric virtual walking with translation gains on gait parameters. The results of the experiment showed significant differences of walking biomechanics in the virtual and real world, and we also found a significant effect of translation gains on most gait parameters.

Our results provide novel insights into effects on gait that can be expected when practitioners in the field of VR follow the suggestions in previous literature to slightly increase virtual walking velocities in order for them to be estimated as more natural by users. Our findings seem to disagree with these suggestions and indicate that a closest match of gait in the real and virtual world can be found for an isometric mapping, whereas nonisometric mappings correlated with often symmetrically-shaped detriments, both for up- and down-scaled virtual walking velocity.

For future work, we aim to study the biomechanics of virtual walking with further visual information about self-motion by incorporating a tracked virtual model of the participant's body. Considering that participants in our experiment tended to look down toward the floor when the virtual walking velocity was reduced, providing such a visual self-representation might help users to acquire a more stable gait profile in VEs. Another possible explanation for the underestimation is the relatively small FOV in most HMDs, but this can still provide a fairly robust and meaningful way to interact with virtual spaces.

We will repeat these experiments with other user groups affected by different cognitive and motor disabilities in order to compare differences in biomechanics and velocity while walking in a VE. Furthermore, we plan to develop different techniques, multimodal illusions, and feedback, which support users in adapting their biomechanics while walking in the VE to the corresponding biomechanics in the real world.

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