

Analyses of Gait Parameters of Younger & Older Adults during (Non-)Isometric Virtual Walking

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Abstract—Understanding real walking in virtual environments (VEs) is important for immersive experiences, allowing users to move through VEs in the most natural way. Previous studies have shown that basic implementations of real walking in virtual spaces, 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 user's physical locomotion. However, these findings have been reported in most cases only for young persons, e. g., students, whereas older adults are clearly underrepresented in such studies. Recently, virtual reality (VR) has received significant public and media attention. Therefore, it appears reasonable to assume that people at different ages will have access to VR, and might use this technology more and more in application scenarios such as rehabilitation or training.

To better understand how people at different ages walk and perceive locomotion in VR, we have performed a study to investigate the effects of (non-)isometric mappings between physical movements and virtual motions in the VE on the walking biomechanics across generations, i. e., younger and older adults. Three primary domains (pace, base of support and phase) of spatio-temporal parameters were identified to evaluate gait performance. The results show that the older adults walked very similar in the real and VE in the pace and phasic domains, which differs from results found in younger adults. In contrast, the results indicate differences in terms of base of support domain parameters for both groups while walking within a VE and the real world. For non-isometric mappings, we found in both younger and older adults an increased divergence of gait parameters in all domains correlating with the up- or down-scaled velocity of visual self-motion feedback. The results provide important insights into the design of future VR applications for older adults in domains ranging from medicine and psychology to rehabilitation.

Index Terms—Virtual Environments, Real Walking, Older Adults, Translation Gains, Biomechanics, Gait.

1 INTRODUCTION

VIRTUAL reality (VR) technologies are an effective way to simulate virtual worlds that are used in many application domains requiring a high degree of immersion and interactivity. In a virtual environment (VE), the user interacts with a multisensory computer-generated environment, which can be explored in real time. In this context, walking as a means to explore the VE is an essential part of a VR experience. Walking is often considered the most basic and natural form of locomotion humans can perform. Thus, realizing real walking in VEs is essential to support a veridical model of reality in a wide range of application domains such as training, rehabilitation, or entertainment. In previous studies, walking in VEs by means of real walking was analyzed in terms of navigation performance [1], [2], gait performance [3] or presence [4] with a focus on younger adults. In our previous work [5], we presented an experiment that focuses on younger

adults, which evaluated the differences of biomechanical walking parameters between a real and virtual environments.

Many studies demonstrated the potential of VR technology for older adults, and presented opportunities and benefits for several application domains ranging from medicine and psychology to rehabilitation [6], [7], [8], [9]. However, most of today's VR systems and applications are mainly used by younger people, whereas older adults are often not considered in applications or scientific experiments using VR technology. Recently, VR has received enormous attention by the general public, and the technology is getting widely used and accessible. Therefore, it appears reasonable to assume that more and more people at different ages will have access to VR, and use VR in the context of applications domains such as rehabilitation or physiotherapy. Hence, we believe that it is important to investigate walking in VEs involving older adults, with the goal to understand the perceptual and motor differences, but also to gain similar advantages from virtual walking as from walking in the real world for the older generation.

During walking in the real world, vestibular, proprioceptive, and visual information create a consistent multi-sensory representation of a person's self-motion, i. e., acceleration, speed and walking direction. Discrepancies between visual feedback and the vestibular-propriocceptive system, such as occurring while using walking-in-place [4], [10], treadmills [11], [12] or VirtuSpheres [13], have been hypothesized to cause detriments in walking performance [14].

Implementing real walking in VEs typically requires tracking the head movements of a user to change the virtual camera

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and generate self-motion feedback, e. g., by means of an *isometric mapping* (sometimes called a one-to-one mapping [15]). In this approach, users may wear position and orientation tracked head-mounted displays (HMDs) that allow the virtual movement to match their physical movement with visual motion cues. A tracked change of the user's position is defined by the vector $T = P_{cur} - P_{pre}$, where P_{cur} is the current position and P_{pre} is the previous position. T is applied one-to-one to the virtual camera, i. e., the virtual camera is moved by $|T|$ units in the corresponding direction in the VE coordinate system. While it seems easy to implement, previous experiments found that such isometric mappings are often not estimated as entirely natural or realistic by users. Williams et al. [16] introduced *translation gains*, to describe the ratio between a virtual translation and the corresponding translation of a user in the real world, i. e., $g_t := \frac{T_{virtual}}{T_{real}}$. Translation gains $g_t \in \mathbb{R}$ provide a way to formalize *non-isometric mappings*, in which a translation T in the real world can be mapped to a scaled translation $g_t \cdot T$ in the VE. This is particularly useful if the user wants to explore VEs whose size significantly differs from the size of the tracked space. For instance, if $g_t = 1$ the virtual scene remains stable considering the head's position change. In the case $g_t > 1$ the displacement in the virtual scene is greater than in the lab space, whereas a gain $g_t < 1$ causes a smaller displacement in the virtual scene compared to the displacement in the lab space.

In a psychophysical experiment using a two-alternative forced-choice task, Stenicke et al. [18] analyzed at which point of subjective equality (PSE) 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 them to estimate them as identical [18]. 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% [19] or by 36% [20]. Most researchers tried to explain these effects by 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 [18], [19], [20]. In a previous study, it was shown that simple gait parameters like walking velocity, stride length, stride frequency were affected in both healthy younger and older adults when visual flow was manipulated [38]. However, this study was limited to a simple optic flow stimulation in the VE, and did not consider important gait parameters such as step width or double support.

In the scope of this article, we analyze differences in several gait parameters while walking within a VE and the real world, and furthermore investigate differences between these parameters in younger and older adults. We believe that it is important to understand how walking in VEs varies across generations. For instance, it has previously been found that walking in a VE for younger adults will result in decreases in walking velocity, increases in step width, and increases in double support compared to the real world. We assume that older adults will show less stability during walking within a VE compared to the real world, in particular, in comparison to younger ones, as a result of various factors such as increased fear of falling, slower sensory-motor coupling or less visual accuracy.

There are several technical and perceptual challenges for real walking in VEs [21]. In particular, illusions related to visual flow may change the user's perception of his self-motion in the VE

independently of his actual self-motion in the VE [22]. This may be used to tune virtual locomotion cues in order to provide natural perception of self-motion in VEs. As described above, younger or older adults might estimate a slightly increased virtual walking velocity as more natural, but we have to consider that this does not necessarily lead to the situation in which the biomechanics of walking in the VE match those of the corresponding behavior in the real world. Unfortunately, the existing body of literature does not provide a consistent understanding of the effects of isometric or non-isometric walking conditions on gait detriments in VEs, or any information on the effects of age on these parameters [14], [23], [24].

In this article, we present an experiment in which we investigate the effects of isometric and non-isometric walking with an HMD on gait parameters of younger and older adults. Our main contributions are:

- Analysis of gait parameters indicating a closest match between virtual and real walking for an isometric mapping, while non-isometric mappings resulted in often symmetrically-shaped detriments both for up- and down-scaled virtual velocity.
- Evaluation of the effects of manipulated visual self-motion on walking biomechanics between younger and older adults, using three domains of spatio-temporal gait parameters that may facilitate understanding of gait performance while walking within a VE and the real world.

2 RELATED WORK

2.1 Biomechanics of Walking

The analysis of the biomechanics of walking provides spatio-temporal parameters that describe global aspects of gait. A typical human gait is defined by a coordinated series of movements. It is divided into two main phases: the stance phase (when the two feet are on the ground, comprising about 60% of the gait cycle) and the swing phase (when one foot is on the ground, comprising about 40% of the gait cycle) [24]. Within a stance phase, the double support represents approximately 20% [44], [45], and single support represents approximately 40% of the gait cycle [46]. 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 spatial, temporal and phasic parameters of gait have to be considered such as velocity, step length, step frequency.

Biomechanical characteristics of gait instability have been fairly well studied. Many experiments examined whether there are age-related changes in gait patterns. Two studies [35], [36] have investigated performance of gait stability with walking experience in the real world, and indicate that older adults walk as stable as or less stable than young adults. It is interesting to investigate whether similar differences can be found when younger or older people walk through VEs.

2.2 Walking in VR

The study of locomotion and perception is the focus of many research groups analyzing walking in both real and virtual environments [14], [24], [25]. The perception of and interaction with



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

virtual worlds may be influenced not only by visual information but also physiological information from the inner body senses. Hence, it is important to investigate contingencies that exist among the sensory and motor information that signal self-motion [26] and differences between biomechanical parameters while walking in the real world versus within VEs [23]. In particular, in this context Mohler et al. reported that walking parameters may affect a user's perception of virtual space [23]. Discrepancies between perception in real and virtual environments have naturally been suggested as a potential factor contributing to the fact that distances in VEs are often over- or underestimated [27], [28], [29], [30]. However, interaction with the VE by walking with visual feedback has recently been shown to drastically improve perceived distance to within 90-100% of actual distance with an appropriate interaction [31], [32], [33], [34]. Furthermore, Ruddle and Lessels [2] found that real walking in a VE provides near-perfect performance on a navigational search task, whereas joystick directed travel resulted in less than 50% of trials performed perfectly.

Several studies investigated the potential to increase the naturalness of virtual walking velocities in VEs for younger adults [41], [42]. For example, Banton et al. 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 [19]. They reported that the visual flow velocity had to be increased by about 50% in a VE to appear natural. 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 [18]. Similarly, users tend to underestimate travelled distances in VEs [43]. Experiments by Steinicke et al. showed that users estimate the virtual distance as smaller than the physical perceived distance against the applied velocity gains [18]. A study performed by Durgin et al. suggested that discrimination of visual velocities near walking velocity is enhanced by the act of walking [41].

Many researchers [14], [17], [26] have investigated physiological and biomechanical aspects of walking across different samples in an attempt to describe real and virtual environments while walking with and without the HMD. Mohler et al. reported that gait parameters (such as velocity, stride length, head angle, etc.) within a VE are different than those in the real world [23]. Furthermore, others found that visual information is associated with

the control of locomotor behavior [17], [47]. In particular, they found that gait velocity of self-motion is influenced by visual flow. Hollman et al. examined the effect of VEs on gait and found that walking in VEs induces changes in kinetic gait parameters (such as weight acceptance peak and push-off peak forces), which reflects compensatory efforts to control the body's center of mass over the base of support during locomotion and, therefore, representing gait instability induced by visual stimulation in VEs [3]. 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, and in how far differences between younger and older adults can be found presuming that these differences exist.

2.3 Gait Analyses for Younger and Older Adults

While several previous studies examined gait in a VE [14], [23], [24], [37], most of those focused on young adults. According to Chou et al. [38], older adults show a comparable ability to integrate visual flow information into a VE for assessment of walking velocity and heading direction. Furthermore, Schubert et al. [39] could not find significant differences in locomotion between younger and older adults due to changes in visual information, especially when visual flow speed decreases, walking velocity and stride length increase; decreasing visual flow speed shows opposite effects. A study by Berard et al. examined whether advanced age could impact on the directing of locomotion in response to changes in visual flow speed in the VE, and found that older adults were impaired to use visual flow cues to direct their locomotion [40]. Whether older adults are more dependent on visual flow information during locomotion compared to younger adults is still open to further investigation.

3 EXPERIMENT

In this section, we describe the experiment in which we have examined how walking in VEs differs from walking in the real world in terms of biomechanics for younger and older adults. Since it has shown (cf. Section 2) altering the visual speed changes gait parameters in younger adults, we tested different isometric and non-isometric walking conditions using the method of translation gains (cf. Section 1) along a straightforward movement

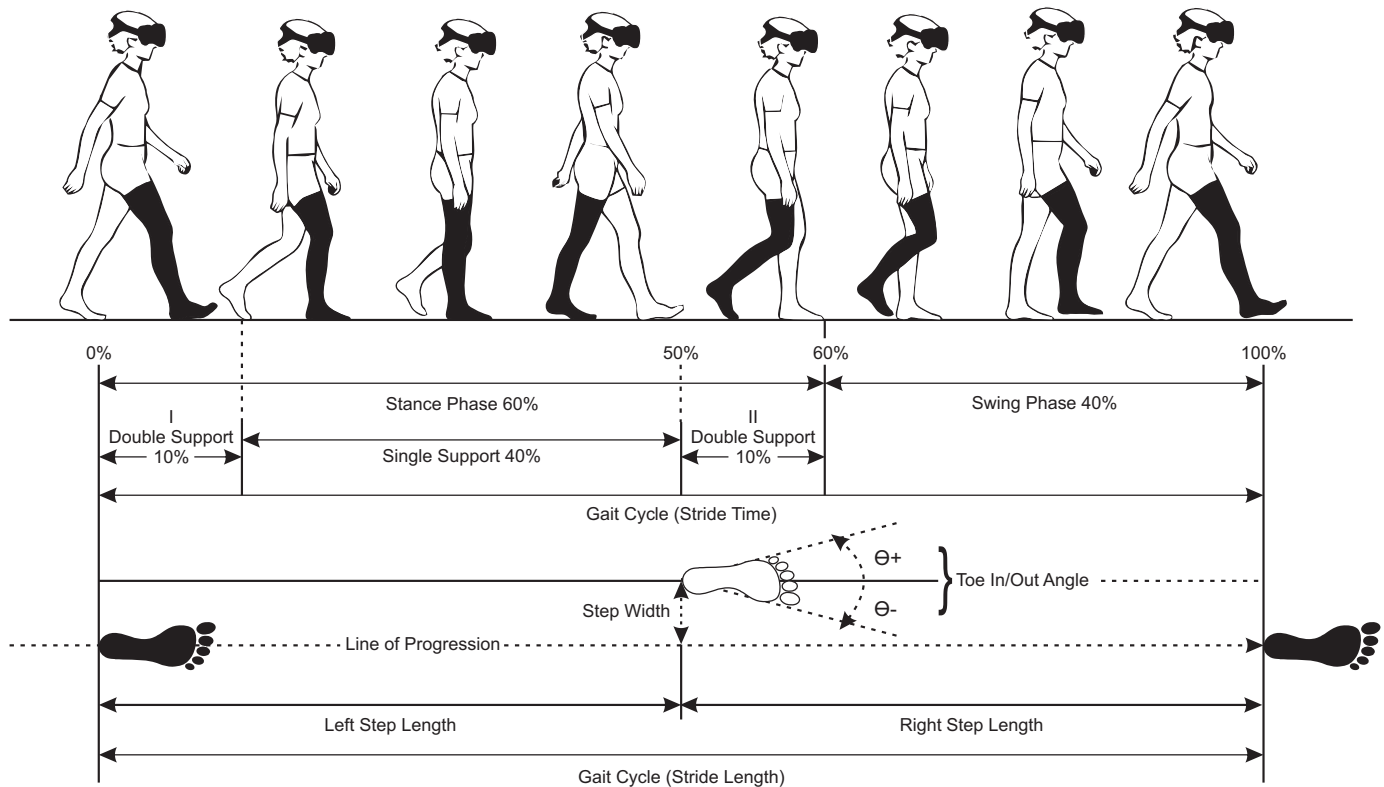


Fig. 2: Spatio-temporal gait parameters measured during the experiment.

path for both younger and older adults. We compared the results to a baseline condition, which was walking in the real world, and with those results from younger and older adults performing the same task. Prior to the experiment, we received approval for the experimental procedure, material, and methods from our institutional review board.

3.1 Participants

A total of 42 healthy participants completed the experiment consist of two groups: 21 younger adults (4 female and 17 male, ages 18 – 34 years, $M = 23.67$ $SD = 4.04$, heights 164 – 196 cm, $M = 180.04$ cm $SD = 8.84$ cm) and 21 older adults (12 female and 9 male, ages 45 – 83 years, $M = 55$ $SD = 10.08$, heights 158 – 192 cm, $M = 174.2$ cm $SD = 9.98$ cm). The younger participants were students or members of the department of computer science or the department of neurophysiology. Students obtained class credit for their participation. The older participants were relatives of patients of the department of neurology or members of the department of neurophysiology and pathophysiology. All of our participants had normal or corrected-to-normal vision. During the experiment, 3 of the younger and 13 of the older participants wore glasses. None of our participants reported a disorder of equilibrium, vision disorders, or other abnormalities (e.g. arthritis, Parkinson's). Participants wore an HMD for approximately 30 minutes during the experiment, Six younger participants had prior experience with HMDs, whereas none of the older participants had prior experience with HMDs. We measured the leg length of our participants before the experiment: younger adults (92 – 111 cm, $M = 98.57$ cm $SD = 5.52$ cm), and older adults (90 – 115 cm, $M = 100.83$ cm $SD = 6.54$ cm). We used the leg length of each participant to calculate a functional ambulation performance (FAP) [48], which represents a quantification of

participants' gait based on a selection of spatio-temporal parameters obtained at a self-selected velocity [49], [50]. 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 step width. 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 experimental trials in order to minimize effects of exhaustion or lack of concentration. The total time per participant, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing, was about one 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(a). 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 VE was rendered using Unity3D; a cross-platform game engine with a custom-enabled VR communications and rendering library. As illustrated in Figure 1(b), the VE showed a virtual pathway of $15\text{m} \times 2.5\text{m}$. 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 had been instructed to walk from the start line to the target (i.e., stopping between the two target lines). 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 HTC Vive HMD for the stimulus presentation, which provides a resolution of 1080×1200 pixels per eye with a refresh rate of 90Hz and an approximately 110° diagonal field of view (FOV). The HMD uses more than 70 sensors

including a MEMS gyroscope, accelerometer and laser position sensors. We tracked sensors on the HMD using a Lighthouse tracking system (2 base stations emitting pulsed IR lasers) that tracked the user's head movement with sub-millimeter precision in the laboratory.

While walking, temporal (timing) and spatial (2D geometric indicators of the participant's feet) gait parameters were measured using a GAITRite electronic walkway system [51]. The GAITRite consists of a walkway with overall dimensions of 90cm \times 7m \times 3.2mm on which the participant walks. A computer system controls the GAITRite and analyzes the data. The GAITRite walkway system provides an active walking area of 60cm \times 6.1m with a scanning frequency of 60Hz. In addition to the active 6.1m long walkway, there are initial 20cm and final 70cm inactive sections to allow for walk on/off areas of the participant (i.e., where the start and target lines were placed). 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 6dpi. The walking distance was 6 meters in all conditions.

3.3 Design

A mixed factorial design was used, with two levels of age group (younger, older) as the between-subjects factor and seven levels of translation gains (cf. Section 1) as the within-subjects factor. The tested translation gains were in the following range: $g_t \in \{\frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1, \frac{5}{4}, \frac{3}{2}, \frac{7}{4}\}$, i.e., visual flow presented at lower $g_t < 1$, matched $g_t = 1$ or higher speed $g_t > 1$. Hence, the experiment consisted of eight walking conditions, i.e., one real-world condition and seven translation gain conditions while participants wore the HMD. Each condition was repeated twice and the order of the tested translation gain conditions was randomized. Hence, each participant completed 16 walking trials. The experiment was conducted in two blocks, the first block with 21 older participants, and the second block with 21 younger participants.

3.4 Procedure

Prior to the walking tasks, participants filled out an informed consent form and received detailed instructions on how to perform the task. In addition, they filled out the simulator sickness questionnaire (SSQ) [52] 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, sweating, fatigue, vertigo, and burping. Participants rated these symptoms on a Likert-type scale [53] from none, slight, moderate, to severe. After the experiment, they filled out a demographics questionnaire as well as the Slater-Usoh-Steed presence questionnaire (SUS PQ) [54].

The task was to first assume the start position by standing in an orthostatic pose at the start line. Then, participants were instructed to walk at a normal pace along the walkway of the GAITRite system while coming to a halt between the location of the target lines (see Figure 1). This was done with and without the HMD. After each trial, the participant had to walk back to the starting point with their eyes open in the real world. During the experiment, an experimental assistant managed the cables of the HMD for each participant and ensure that participants could walk safely.

3.5 Gait Data

Several spatio-temporal gait parameters (i.e., time and distance variables of the gait cycle) are analyzed through the GAITRite walkway system. The mean of consecutive gait cycles measured during steady-state walking was $M = 3.77$ $SD = 0.5$ for younger adults, and $M = 4.42$ $SD = 0.6$ for older adults. As illustrated in Figure 2, these parameters are:

- *Velocity* the distance travelled by the body divided by the ambulation time. It is measured in centimeters per second (cm/sec).
- *Cadence* the number of steps taken while a person walks, expressed in steps per minute (steps/min).
- *Step length* the distance between corresponding successive placements of the opposite foot. The unit of measure is centimeters (cm).
- *Step width* the lateral 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 cm.
- *FAP score* derived by subtracting points from a maximum score of 100 for walking at a self-selected velocity [50]. 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 average between right and left dynamic base of support during ambulation, B is the degree of asymmetry of the participant's gait expressed as the ratio between 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.

- *Double support* the amount of time that a participant spends with both feet on the ground during one gait cycle.
- *Single support* 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 equivalent to the swing time.
- *Stance phase* the portion of the gait cycle when the foot is in contact with the ground:

$$StancePhase = 2 \cdot DoubleSupport + SingleSupport \quad (2)$$

- *Swing phase* is the portion of the gait cycle when the foot is in the air:

$$SwingPhase = SingleSupport \quad (3)$$

4 RESULTS

Figures 3 to 5 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 1):

4.1 Real and Virtual Walking Comparisons

In order to compare the effects of walking in a VE with walking in the real-world conditions we first considered only the data in the conditions while wearing the HMD in which the virtual walking

TABLE 1: The results of statistical analysis

	Younger adults			Older adults			Mixed ANOVA with post-hoc			
	M_{SD}	$t(20)$	p	M_{SD}	$t(20)$	p	Source	F	p	η_p^2
Velocity (cm/sec)	116.42 _(13.28) ^r	3.35	.003	107.92 _(12.01) ^r	-.78	.445	gain	(3.63, 145.21) = 25.82	< .001	.392
	108.86 _(13.94) ^v			109.72 _(10.44) ^v			group	(1, 40) = .02	.874	.001
								post-hoc	$g_t(.25)_{5,.75,1.75}$ $g_t(.5,.75,1)_{1.25,1.5,1.75}$ $g_t(1.25)_{1.5,1.75}$ $g_t(1.5)_{1.75}$	< .02
Cadence (steps/min)	105.29 _(7.54) ^r	.563	.58	104.88 _(7.52) ^r	-2.166	.043	gain	(3.23, 129.14) = 22.16	< .001	.356
	104.53 _(8.17) ^v			107.26 _(7.83) ^v			group	(1, 40) = .50	.482	.012
								post-hoc	$g_t(.25)_{1.5,1.75}$ $g_t(.5,.75)_{1.25,1.5,1.75}$ $g_t(1,1.25)_{1.5,1.75}$ $g_t(1.5)_{1.75}$	< .01
FAP score	95.73 _(3.51) ^r	3.039	.006	82.97 _(18.38) ^r	1.088	.290	gain	(4.25, 169.79) = 6.06	< .001	.132
	92.78 _(4.49) ^v			81.92 _(18.44) ^v			group	(1, 40) = 7.36	.010	.155
								post-hoc	$g_t(.5,.75,1,1.25,1.5)_{1.75}$	< .01
Step length (cm)	66.29 _(4.44) ^r	4.84	< .001	61.73 _(5.12) ^r	.309	.76	gain	(3.51, 140.36) = 13.63	< .001	.254
	62.45 _(5.19) ^v			61.47 _(5.11) ^v			group	(1, 40) = .53	.471	.013
								post-hoc	$g_t(.25)_{5,.75}$ $g_t(.5,.75,1,1.25)_{1.5,1.75}$ $g_t(1.5)_{1.75}$	< .02
Step width (cm)	10.19 _(3.08) ^r	-3.056	.006	9.72 _(2.41) ^r	-3.861	.001	gain	(4.19, 167.49) = 5.20	< .001	.115
	11.49 _(3.05) ^v			11.10 _(2.74) ^v			group	(1, 40) = .48	.492	.012
								post-hoc	$g_t(.25)_{1,1.25,1.5}$	< .03
Toe in/out (deg)	4.61 _(3.84) ^r	-4.064	.001	5.54 _(3.98) ^r	-2.534	.020	gain	(5.21, 208.55) = 7.05	< .001	.150
	6.42 _(4.61) ^v			6.46 _(4.44) ^v			group	(1, 40) = .009	.923	.001
								post-hoc	$g_t(.5)_{1.25,1.5,1.75}$ $g_t(.75)_{1.5,1.75}$	< .008
Double support (%)	21.91 _(2.75) ^r	-3.278	.004	24.89 _(2.78) ^r	-.906	.376	gain	(3.82, 152.76) = 1.36	.251	.033
	23 _(2.61) ^v			25.41 _(3.39) ^v			group	(1, 40) = 5.84	.020	.127
Single support (%)	39.06 _(1.22) ^r	4.02	.001	37.22 _(1.36) ^r	.258	.799	gain	(2.92, 116.86) = 1.60	.193	.039
	38.29 _(1.41) ^v			37.18 _(1.29) ^v			group	(1, 40) = 4.92	.032	.110
								post-hoc	$g_t(.25)_5$	< .002
Stance phase (%)	60.94 _(1.22) ^r	-4.135	.001	62.77 _(1.5) ^r	-.321	.752	gain	(3.16, 126.26) = 1.66	.177	.040
	61.71 _(1.40) ^v			62.83 _(1.29) ^v			group	(1, 40) = 5.79	.021	.126
								post-hoc	$g_t(.25)_5$	< .002

^r Real environment^v Virtual environment

velocity matched the real-world walking velocity, i. e., 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 between real world and VE in younger adults group on walking velocity $t(20) = 3.35$, $p = .003$, FAP score $t(20) = 3.039$, $p = .006$, step length $t(20) = 4.840$, $p = .001$, step width $t(20) = -3.056$, $p = .006$, toe in/out $t(20) = -4.064$, $p = .001$, double support $t(20) = -3.278$, $p = .004$, single support $t(20) = 4.020$, $p = .001$ and stance phase $t(20) = -4.135$, $p = .001$. The only dependent variable showing no significant effect of immersion was cadence $t(20) = .563$, $p = .580$.

On the contrary, in older adults we did not find any significant effect between real world and VE on walking velocity $t(20) = -.780$, $p = .445$, FAP score $t(20) = 1.088$, $p = .290$, step length $t(20) = .309$, $p = .760$, double support $t(20) = -.906$, $p = .376$, single support $t(20) = .258$, $p = .799$ and stance phase $t(20) = -.321$, $p = .752$. The only dependent variables showing a significant effect between real world and VE were cadence $t(20) = -2.166$, $p = .043$, step width $t(20) = -3.861$, $p < .001$ and toe in/out $t(20) = -2.534$, $p = .020$.

The results show that most gait parameters of the conditions with HMD significantly differ from walking in the real world for the younger adult participants. In contrast for older adults the

results show that most gait parameters of the VE conditions do not significantly differ from walking in the real world.

4.2 Translation Gains Comparisons

We analyzed the results for the different translation gains in the immersive conditions with a mixed ANOVA with age group (younger, older) as the between subject factor and translation gains (i. e., seven levels) as the within subject factor. The results were normally distributed according to a Shapiro-Wilk test at the 5% level. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity in case Mauchly's test indicated that the assumption of sphericity had been violated. For all analyses, post hoc Bonferroni corrections for multiple comparisons at the 5% significance level were used to explore significant effects across all analyses

We found a significant main effect of translation gains on walking velocity ($F_{3.63,145.21} = 25.82$, $p < .001$, $\eta_p^2 = .392$), cadence ($F_{3.23,129.14} = 22.21$, $p < .001$, $\eta_p^2 = .356$), FAP score ($F_{4.25,169.79} = 6.06$, $p < .001$, $\eta_p^2 = .132$), step length ($F_{3.51,140.36} = 13.63$, $p < .001$, $\eta_p^2 = .254$), step width ($F_{4.19,167.49} = 5.20$, $p < .001$, $\eta_p^2 = .115$), toe in/out ($F_{5.21,208.55} = 7.05$, $p < .001$, $\eta_p^2 = .150$). No significant main effect found of translation gains on double support ($F_{3.82,152.76} = 1.36$, $p = .251$, $\eta_p^2 = .033$), single support

($F_{2,92,116.86} = 1.60$, $p = .193$, $\eta_p^2 = .039$), stance phase ($F_{3,16,126.26} = 1.66$, $p = .177$, $\eta_p^2 = .040$).

The main age group effects were significant only for FAP score ($F_{1,40} = 7.36$, $p = .010$, $\eta_p^2 = .155$), double support ($F_{1,40} = 5.84$, $p = .020$, $\eta_p^2 = .127$), single support ($F_{1,40} = 4.92$, $p = .032$, $\eta_p^2 = .110$), stance phase ($F_{1,40} = 5.79$, $p = .021$, $\eta_p^2 = .126$). No significant main effect found of group on walking velocity ($F_{1,40} = .02$, $p = .874$, $\eta_p^2 = .001$), cadence ($F_{1,40} = .50$, $p = .482$, $\eta_p^2 = .012$), step length ($F_{1,40} = .53$, $p = .471$, $\eta_p^2 = .013$), step width ($F_{1,40} = .48$, $p = .492$, $\eta_p^2 = .012$), toe in/out ($F_{1,40} = .009$, $p = .923$, $\eta_p^2 = .001$).

Post-hoc tests (Table 1) showed significant differences for most gait parameters between translation gains within younger and older groups. The results revealed no significant interaction effects between age group and translation gains for all gait parameters.

4.3 Questionnaires

We measured a mean SSQ score of younger adults $M = 11.75$ $SD = 14.45$ and older adults $M = 9.61$ $SD = 12.2$ before the experiment, and a mean SSQ score of younger adults $M = 13.17$ $SD = 21.37$ and older adults $M = 12.64$ $SD = 18.26$ after the experiment. We analyzed the SSQ questionnaire scores with a non-parametric Wilcoxon Signed Rank Test at the 5% significance level. The SSQ 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; younger adults $Z = -1.2$, $p = .23$ and older adults $Z = -.629$, $p = .529$. The mean SUS PQ score for the sense of feeling present in the VE was for younger adults $M = 27.47$ $SD = 5.97$ and older adults $M = 24.61$ $SD = 6.32$ which indicates a high sense of presence [54]. We analyzed the SUS PQ and SSQ questionnaires with a non-parametric Mann-Whitney U Test but found no significant difference between younger and older adults in SUS PQ scores $U = 164.5$, $p = .157$. 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, 5=high fear, younger adults $M = 0.3$ $SD = 1.53$ and older adults $M = 0.8$ $SD = 1.43$).

5 DISCUSSION

The aim of the present study was to investigate whether older adults show differences in gait performance while walking within a VE and the real world compared with younger adults. Based on gait analysis, three domains of gait performance were identified. A pace domain was characterized by walking velocity, step length, and cadence. A base of support domain was characterized by step width, toe in/out (foot angle), and FAP score. A phase domain was characterized by temporal divisions of the gait cycle.

5.1 Gait Pace

Velocity

Figure 3(a) shows that there was no significant difference for older adults between walking velocity while wearing the HMD compared to the real world for translation gain $g_t = 1$. These results are different from results found in younger adults, which show a significant decrease of walking velocity by 6.5% while wearing the HMD compared to the real world, which is similar to results obtained in a previous study performed by [5], who reported a decrease in walking velocity by 6%. The main effects

of translation gain were significant for walking velocity, indicating that both groups increased their walking velocity when the virtual velocity was decreased with a translation gain $g_t < 1$ and a decreased in walking velocity with a gain $g_t > 1$, which indicates an almost asymmetrical effect of applied translation gains between $g_t = .5$ and $g_t = 1.75$. Informal comments by our participants suggest that many of them felt that decreased virtual walking velocity with a gain $g_t = .25$ lead to less stable walking along the path, thus inducing them to slow down even more. It is important to note that the effect of translation gains was actually similar to a previous study by [17] performed on young adults with a slightly different experimental design.

Step Length

Furthermore, Figure 3(b) shows that older adults had comparable step length in the VE and in the real world for $g_t = 1$, whereas younger adults had a significantly shortened step length in the VE than in the real world by 5.7%. The results also reflect a similar response for both groups to visual stimulation during the application of translation gains regardless of whether translation gains $g_t < 1$ or $g_t > 1$ was applied. The performance of older and younger adults was significantly different in the real condition for walking velocity $t(20) = 3.436$, $p = .003$, and for step length $t(20) = 4.436$, $p < .001$. Older adults walked at a slower velocity and with shorter steps by $\approx 7\%$ than younger adults. However, as walking velocity and step length can be modified by cognitive influences [55] or muscle activity [56], it is also likely that the walking performance observed in older people are partly due to a reluctance rather than an inability to walk more quickly.

Cadence

Although both groups exhibited comparable cadence within the real world condition, older adults had a significantly higher step rate in the VE compared to the younger adults. Figure 3(c) shows that older adults had a significant difference in cadence (step rate) by 2.3% while walking within a VE compared to the real world, which implies that the older group took an extra steps in the VE compared to the real condition. This increment in cadence may be attributed to a compensation for the shorter step lengths taken in a relatively shorter period of time. No significant difference for cadence was found in younger adults. In addition, the linear main effects of translation gain for cadence were significant, showing that both groups walked at a higher step rate when the translation gain $g_t < 1$ was applied.

5.2 Base of Support

Step Width

Figure 4(a) shows a significant increase of step width by 14.4% in older adults and 12.8% in younger adults while walking in the VE compared to the real world, which is similar to results obtained in a study performed by [37], who reported an increase in step width by 23% in younger adults. This suggests that both groups tended to spread their feet apart, thereby increasing their step width while walking with an HMD in the VE and a translation gain of $g_t = 1$. Moreover, step width was significantly wider with slower translation gains $g_t = .25$, and was narrower with translation gains $g_t > 1$. 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.

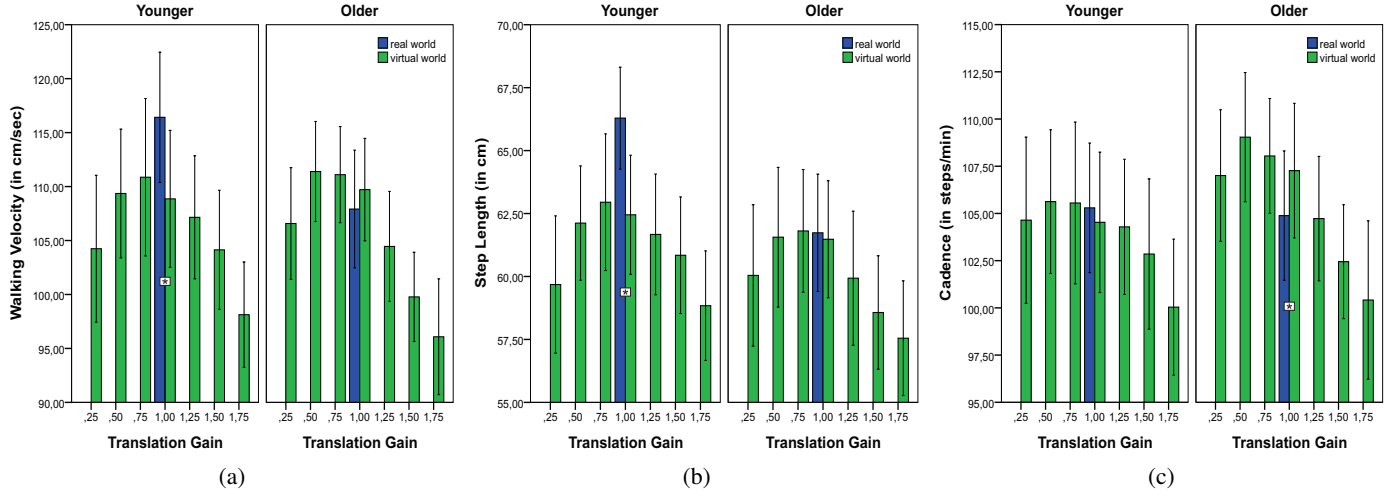


Fig. 3: The pace domain results for applied translation gains on the horizontal axis and pooled for (a) walking velocity, (b) step length and (c) cadence on the vertical axis. The error bars show the standard error.

Toe In/Out

In this scope, we also found that the toe in/out (foot angle) in Figure 4(b) increased positively, which indicates that participants walked with toes pointing further out within the VE. (i. e., the feet are outside the line of progression as shown in Figure 2) In contrast, we did not find any negative angles of toe in/out within the VE, or in the real world.

FAP Score

Furthermore, as shown in Figure 4(c) we found that the FAP score significantly decreased in the VE compared to the real world in younger adults with respect to an isometric mapping with $g_t = 1$, which indicates that the number of points subtracted increased. No significant difference was found in older adults, which justifies their comparable velocity and step length in the real world and the VE. These points deducted in the different parts of the FAP score (see 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 [57], e. g., up to eight points are deducted if the dynamic step width 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 the FAP score calculation, we observed that a greater amount of points for older adults were deducted for dynamic step width and functions of right and left steps. The deductions for asymmetry of step length were nonexistent or close to zero. For younger adults the points were deducted mostly for dynamic step width.

Moreover, the FAP scores were reduced for both groups when non-isometric mappings were applied with translation gains $g_t \neq 1$, which indicates that selected parameters increasingly differed from normal gait. Additionally, the main age group effects were significant for FAP score, indicating that older adults walked at lower FAP score 80.5 than younger adults. This also suggests that older adults showed worse performance with different modulations in walking with response to the availability of translation gains compared with younger adults. This finding can be attributed to the fact that impairments occurred in the individual components

of the FAP score, i. e., dynamic step width and functions of right and left steps led to lower the scores for the older group.

5.3 Gait Phases

A phase domain represents temporal divisions of the gait cycle. Figure 5 shows a non-significant difference between gait phases when older adults walk in the real world compared to walking through a VE. In older adults, double support occupied $\approx 24.9\%$ of the gait cycle, single support/swing phase $\approx 37.2\%$ and stance phase $\approx 62.8\%$. These findings indicate that the durations of gait cycle phases differ slightly from norms established by [58], i. e., double support 24%, single support/swing phase 38% and stance phase 62%, but likely represents the fact that older participants in our study walked with convergent gait pace in the real world and the virtual environment. In contrast, we can see in Figure 5 that younger adults show significant differences between all gait phases while walking in the VE and real world. Double support, in which the body weight is supported by both legs, was prolonged by 5% during VE walking. Single support decreased by 2% and stance phase increased by 1.3%, which justifies why younger adults walked with slower gait speed and shorter steps in the VE compared to the real world.

Moreover, no significant main effects of translation gains were found on all phasic parameters, showing that both group tended to walk during the application of translation gains $g_t < 1$ and $g_t > 1$ with non-significant discrepancies in gait pattern throughout the virtual walking. Post hoc analyses revealed significant differences in single support and stance phase only between translation gains $g_t = .25$ and $g_t = .5$. The effects of age group were statistically significant for all gait phases, indicating that the effects of translation gains were influenced by age. Older adults walked with longer double support 25.6%, less single support 37.4% and a longer stance phase 62.6% than the younger adults.

Generally, it is interesting to note that our findings underline the importance of investigating the differences between gait parameters across generations while walking in the real world and within a VE. Specifically, our results show that the older adults exhibited comparable gait stability in most parameters within the

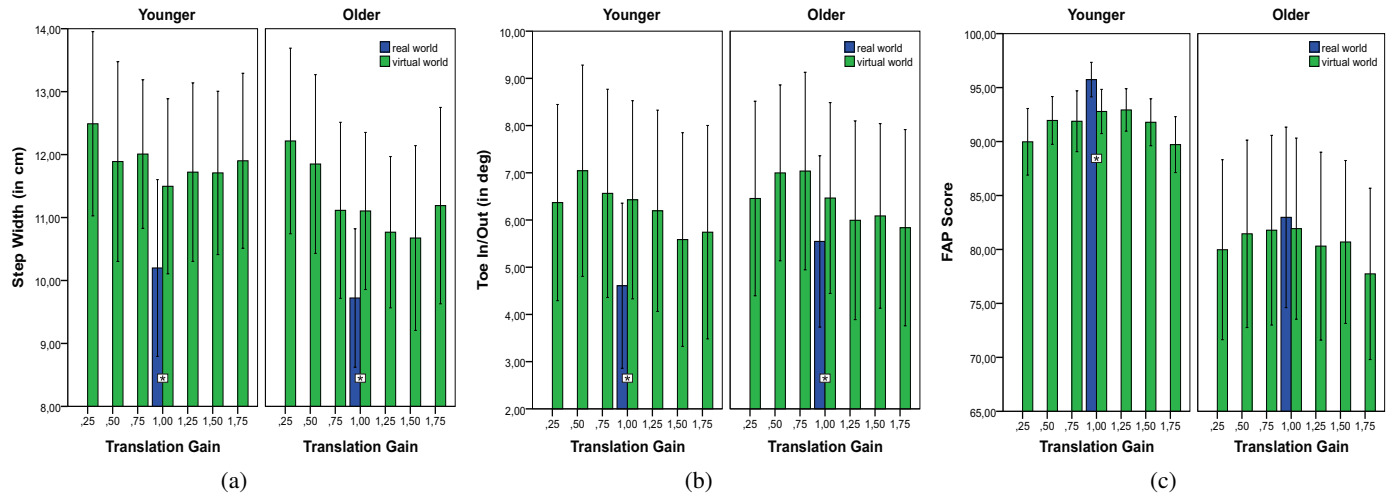


Fig. 4: The base of support domain results for applied translation gains on the horizontal axis and pooled for (a) step width, (b) toe in/out and (c) FAP score on the vertical axis. The error bars show the standard error.

pace and phasic domains during walking with and without the HMD.

The finding of unchanged walking parameters of older adults in the real and VE was an interesting observation. Older adults are known to have a more unstable gait pattern with about 50% of them will suffer recurrent falls while walking [59]. Increased gait variability during walking characterizes gait instability in older adults, which is further worsened with increasing cognitive demands such as dual tasking [60]. One would suggest further deterioration of walking capability by use of VR instead of constant gait performance in real and virtual conditions. In older adults, virtual environments have been found to impose a cognitive load that demands attention, response selection, and the processing of rich visual stimuli involving several perceptual processes [61].

Hypotheses about the unchanged gait performances in older adults in real and the VE remain speculative. It could be suggested that older adults already walk more slowly with decreased step length in the real world, so that the relative change between conditions is not obvious "floor effect". Another explanation could be that the hierarchical process of sensory organization is already altered in older compared to younger adults with another emphasis of the different orientational senses on the motor organization (e. g. less visual or proprioceptive weighting in the older adults). Besides, the older group could use the VR as an "external locus of control" fixing their gaze to the screen and thus walking more stable and faster. Another explanation could be that older adults are more attentive and motivated when using VR technology [62], which invigorates their walking and prevents gait deterioration. Therefore, older adults were not dependent on the presence of visual information during walking compared to younger adults, which induces comparable gait performance in older adults while walking in the VE compared to the real world. Interestingly, we found that older adults modulated their walking speeds within the VE asymmetrically with manipulations of visual flow velocity in much the same manner as younger adults. For example, increasing visual flow with translation gains $g_t > 1$ resulted in a reduced walking velocity and step length as shown in Figure 3 (a, b).

Our findings further suggest that various aspects of gait were found in the base of support domain to maintain stability, which has been a hallmark of unsteady gait [63]. Also, walking in the

VE was found to correlate with widening step width and positive toe-out. While the walking behavior of older adults was similar to young adults in terms of step width and toe in/out, there seems to be little agreement on the idea that an increased step width and foot angle represent a compensatory strategy [64] also correlated to fear of falling [65].

Regarding age group differences in the phase domain as shown in Figure 5, the older group had a 4.6% decrease in the single support phase of the gait cycle compared to the younger group, which directly reflects a decreased step time. Also, a 13.2% increase in the double support phase indicates that older adults spent longer periods with both feet in contact with the ground while walking with and without the HMD.

Confirming previous results [5], younger adults walked significantly different within the real and virtual environments in terms of almost all gait parameters within the tested domains, and most gait differences increased when large discrepancies of virtual velocity were introduced with non-isometric mappings. This might be explained by hardware factors such as the weight, limited FOV and latency of the HMD, which cause a participant to walk differently in the VE. In particular, small FOV and latency could have a greater impacts on younger adults who may be dependent more on the availability of visual information to guide their walking behavior compared to older adults. Although the HTC Vive's end-to-end system latency is low, about 22ms measured between physical movement of the headset and the corresponding update of the Vive's display [66], but still can provides delay from the user's physical movement until the response becomes available on the headset's screen. Another potential explanation for the misinterpretation could be based on incorrect depth and motion cues provided to the human eye, when looking through an HMD, which introduces accommodation-convergence conflicts [67], in particular, in combination with age-related accommodation loss. Watt et al. [68] stated that inappropriate depth cues in typical HMDs may therefore contribute to distortions in perceived space. Or, non-visual factors (e.g., fear of falling or mobility-related anxiety) might be have a greater impacts on older adults compared to younger ones [6].

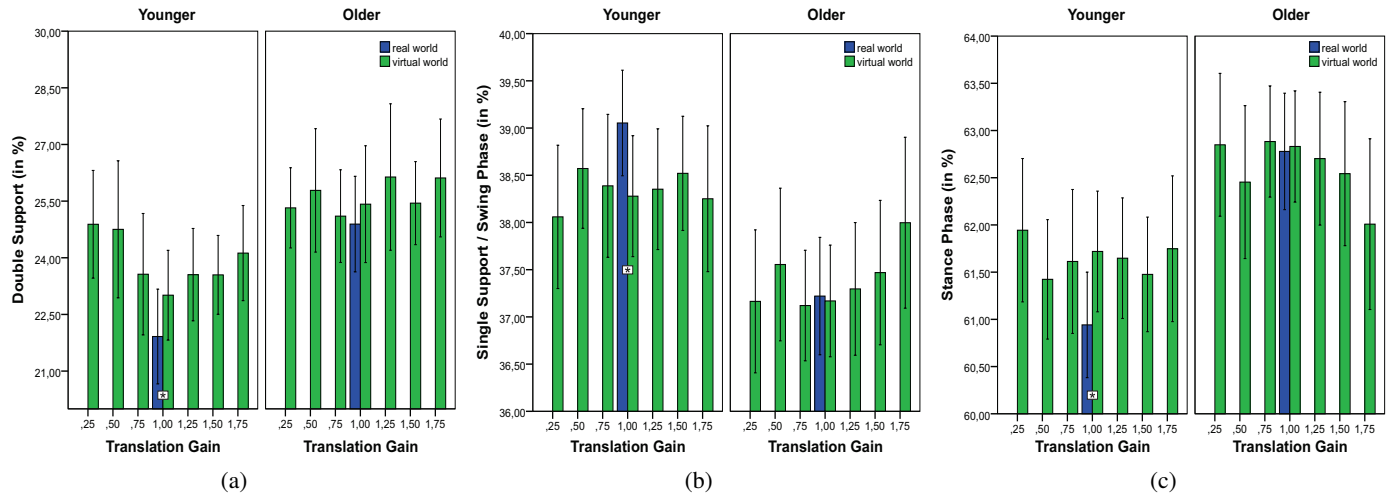


Fig. 5: The phase domain results for applied translation gains on the horizontal axis and pooled for (a) double support, (b) single support/swing phase and (c) stance phase on the vertical axis. The error bars show the standard error.

6 CONCLUSION

In summary, we evaluated the differences of biomechanical walking parameters of younger and older adults between walking in the real world and in the VE. In the VE conditions, we analyzed effects of non-isometric virtual walking with translation gains on gait parameters. Interestingly unlike younger group, the results of the older group showed similar results for the most walking biomechanics in the virtual and real world, and we could not find any significant effects of translation gains on most gait parameters. The results of older adults indicate similar gait patterns in the most parameters within pace and phasic domains in the real and virtual world with an isometric mapping. In contrast, the base of support domain indicated a significant increment in step width and toe in/out angle while walking within the VE.

During the application of non-isometric mappings, we found that most gait parameters within the domains correlated with often symmetrically-shaped detriments both for up- and down-scaled virtual walking velocity. Hence, we neither advocate increasing nor decreasing the virtual walking velocity of the user, but rather suggest maintaining an isometric one-to-one relation whenever possible to minimize gait detriments and the risk of falling. However, such manipulations might be useful when it comes to applications in the area of rehabilitation or physiotherapy.

In principle, we would like to see further studies to explore strategies for measuring an accurate perception of distances in VEs, which do not exactly match a user's actual occupied environment. Since, many researchers have found that the estimation of the travel distance of a simulated movement shows characteristic errors, sometimes overestimating and sometimes underestimating the true travel distance [27], [28], [29], [30]. Another open issue is the effect of adaptation to motion manipulations in VEs. Such adaptive properties of the perceptual system also open up possibilities for manipulation, which have not been investigated yet in this context. Adaptation requires that the user stays and acts within a VE for a longer time. This transforms the user's perception of the VE such that he learns to interact with the VE in a particular way. The potential of these learning effects remains to be explored, which over a longer time period of time that the gait parameters may adapt and become more stable.

For future work, we aim to study the biomechanics of virtual walking in older adult groups, who are affected by different cognitive or motor disabilities (e. g., Parkinson's disease), which support patients in enhancing their motor abilities while walking in a VE. The present work showed some significant differences between biomechanics of walking between younger and older adults, and underlines how important it is to study different users groups with the widespread use of VR technology. Furthermore, the application of translations gains might open up new vistas for rehabilitation or physiotherapy, for instance, in the context of reducing the risk of fall prevention for older adults with cognitive or motor disabilities.

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