Analysis of VR Sickness and Gait Parameters During Non-Isometric Virtual Walking with Large Translational Gain

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ABSTRACT

The combination of room-scale virtual reality and non-isometric virtual walking techniques is promising-the former provides a comfortable and natural VR experience, while the latter relaxes the constraint of the physical space surrounding the user. In the last few decades, many non-isometric virtual walking techniques have been proposed to enable unconstrained walking without disrupting the sense of presence in the VR environment. Nevertheless, many works reported the occurrence of VR sickness near the detection threshold or after prolonged use. There exists a knowledge gap on the level of VR sickness and gait performance for amplified non-isometric virtual walking at well beyond the detection threshold. This paper presents an experiment with 17 participants that investigated VR sickness and gait parameters during non-isometric virtual walking at large and detectable translational gain levels. The result showed that the translational gain level had a significant effect on the reported sickness score, gait parameters, and center of mass displacements. Surprisingly, participants who did not experience motion sickness symptoms at the end of the experiment adapted to the non-isometric virtual walking well and even showed improved performance at a large gain level of 10x.

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Index Terms: Virtual Reality—Cybersickness—;——Locomotion—Walking—NavigationRedirected Walking

1 INTRODUCTION

Virtual reality (VR) is becoming a major medium for content consumption and social interaction. However, one major issue that impedes the adoption of VR technologies is the occurrence of *VR sickness*, which causes symptoms similar to motion sickness (MS), such as headaches, nausea, vomiting, drowsiness, and disorientation [1,10,11,28,36]. Earlier results from Stanney and Kennedy [44] reported that while using VR, 80% of users experienced some symptoms of sickness, with up to 50% experiencing such severe symptoms that the VR session had to be terminated immediately. Previous research [32, 33, 52] reported that repeated exposure to the virtual environment could increase users' resilience to VR sickness. However, experiencing the discomfort of VR sickness might discourage even the most curious users from ever using VR again.

The combination of the room-scale VR and redirected walking techniques has received a lot of attention in the research community. The high-precision and low-latency room-scale head tracking system enables the rendering of correct parallax effect as well as the navigation of the virtual environment through natural walking, which minimizes the potential sensory conflicts between a user's visual perception of the virtual environment and the sensory input of their vestibular system [33, 52]. The redirected walking techniques overcome the constraint of the physical space around the users and extend the coverage of the virtual space by adaptively amplifying and/or warping the mapping between the real and virtual space without users awareness [27, 46, 47, 48, 53]. Sun et al. [48] combined the detection of saccadic suppression and redirection techniques and achieved an impressive result of mapping a confined 3.5 m x 3.5 m real room to a much larger 6.4 m x 6.4 m synthetic virtual space.

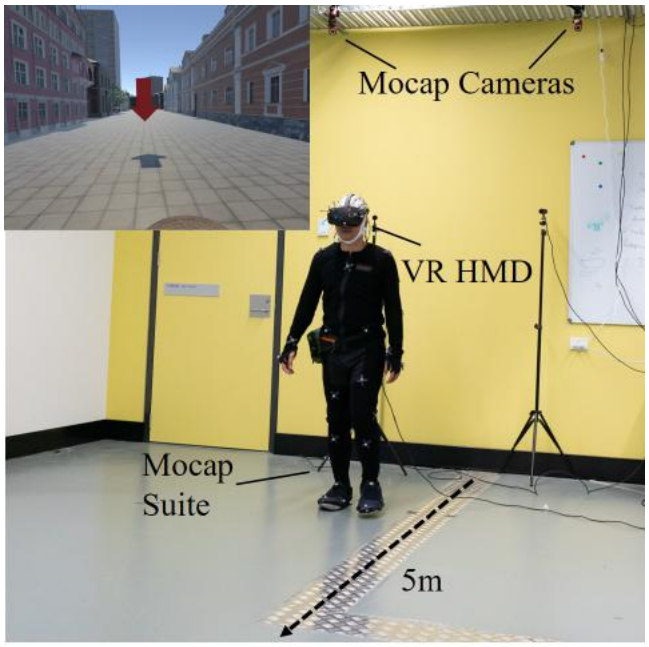

Figure 1: Experiment setup for non-isometric virtual walking.

Few works have systematically investigated VR sickness induced by redirected walking techniques. This is understandable because most research efforts have been dedicated to finding a balance between the intensity of perception manipulation and the probability of users' noticing the underlying alteration of the virtual space [16,33,46]. Multiple works [21,53] have reported performance decreases and the occurrence of motion sickness symptoms at the gain value range between 1.5X to 2.0X, where gain value represents the mapping between the physical and the virtual world. However, there is a knowledge gap regarding the relationship between the level of gain values and the severity of VR sickness, especially at a larger gain value. We argue that redirected walking techniques with larger, and noticeable, gain values is worthwhile. For example, a user might find virtual walking with a large translational gain more natural than other navigation metaphors such as teleportation, flying, or moving on a belt [33]. A user might also tolerate a temporary break of the sense of presence in exchange for a faster travel via natural walking in the virtual environment. We believe understanding the impact of non-isometric virtual walking techniques at a wider range of gain values - even well beyond the detection threshold [16] - will enable a more comprehensive integration of redirected walking into different navigation techniques in VR.

This paper presents an experiment that investigated VR sickness and gait parameters during the non-isometric virtual walking experience, particularly at large and detectable translational gain (TG) levels. Figure 1 shows the experiment setup. The participant wore a VR head-mounted display (HMD) and a full-body motion capture

suit, which enabled the recording of gait parameters (i.e., stepping distance and cadence) and center of mass (CoM) displacement. During the experiment, the participant was instructed to walk toward a destination marked by a red arrow and back to the original position on a virtual street in the city of Sydney with six different levels of translational gain at an increasing order $\{1,2,4,6,8,10\}$ (Figure 2). We hypothesized that TG would have a main effect on the perceived level of VR sickness and on CoM displacement and gait performance. More specifically, we hypothesized that participant would experience more severe VR sickness symptoms, larger posture instability, and decreased gait performance as TG increases.

2 Related Works

2.1 VR Sickness

Despite the advancement of head-mounted display hardware, a large portion of VR users still experience VR sickness symptoms such as headaches, nausea, vomiting, drowsiness, and disorientation [10, 28, 36]. Stanney et al. [45] reported that compared to traditional motion sickness, VR sickness can be three times more severe and exhibits a different symptom profile. Among various theories for the cause of VR sickness [28], the sensory conflict theory has been the most widely accepted [24, 25, 28]. The sensory conflict theory argues that the cause of VR sickness is the conflict between sensory input systems engaged in the virtual environment. For example, when experiencing a VR roller coaster in a stationary setup, a sensory conflict arises because the visual system perceives a forward-moving optical flow pattern, while the vestibular system does not sense a proportional linear or angular motion. Another competing theory for VR sickness focused on the postural instability and argued that decreased postural stability magnifies cue-conflicts that underlie sickness symptoms [8, 39].

The research community has long been aware of VR sickness [10, 12, 38] and has proposed a stream of creative methods to reduce the sickness symptoms [3, 13, 34, 51]. Many preventative approaches reduce the occurrence of sensory mismatch. For example, navigating the virtual environment with a point and teleportation method that relocates the user immediately to the selected destination [6] or applying blurring [35] and vignetting [13] in peripheral vision, which has high motion sensitivity, to reduce the perceived visual motion. Another prominent technique is galvanic vestibular stimulation (GVS) which applies an electrical current to stimulate vestibular afferent nerves and recouple visual and vestibular cues [7, 14, 56]. Notably, most of these previous works focused on stationary VR setups. The users usually remained relatively stationary on a seat and the sensory conflicts were created through the visual motion patterns on 2D displays or head-mounted displays.

2.2 Redirected Walking

Natural walking in VR provides a superior VR experience, yet the navigable area is constrained by the physical space around the user. Nilsson et al. [33] categorized techniques for overcoming the physical space constraint for natural walking into three classes: repositioning, proxy gestures, and redirection techniques. Repositioning techniques leverage different types of treadmill systems, such as motorized treadmills [19] and frictionless omni-directional treadmills [49], to offset the users forward movement and keep the user at the same position. Proxy gestures techniques drive movements in the virtual environment through proxy gestures resembling real walking, such as upper arm waving [30, 31], head tilt [50], and walk-in-place [43]. Redirection techniques manipulate the users actual walking path in the real world, without being perceived by the user, to exploit the limited physical space. Path manipulation is achieved either by dynamically scaling user motion [46, 53] or by updating the virtual environment [5, 15, 47, 48].

This paper investigates the redirection technique that extends the physical space by amplifying the mapping between physical and virtual movement, which is called translational gain. This is a popular technique in VR [2, 18, 23, 37, 46] because of its simplicity and its preservation of the natural walking and vestibular self-motion information. Previous papers have examined the impact of translational gain on gait parameters [23] as well as on object selection performance [53]. It has been shown that there is a detection threshold around 1.25x for translational amplification and 1.5x for rotational amplification [16, 46]. However, it is unclear how exposure to large perceivable translational gains would affect the user's perception and gait performance.

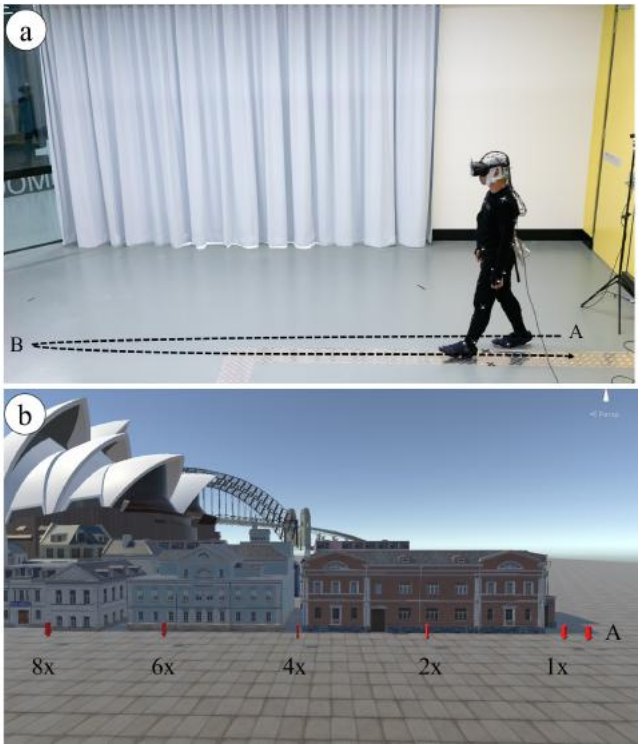

Figure 2: (a) Physical environment for the experiment, and (b) corresponding virtual environment with red arrows indicating the end point of the trials at different translational gains.

3 Experiment

This experiment investigated the correlation between the level of translational gain of virtual walking and the severity of VR sickness. Complementing previous works that examined the usability of translational gain ranges below 3x [2, 18, 22, 37, 46, 53], our experiment examined a larger gain range from 1 to 10 and focused on how VR sickness affected the behavior of the users performing virtual walking while wearing an HMD.

3.1 Participants

Twenty one healthy adults (17 males, 4 females) participated in the experiment. The mean age was 25.73, with a standard deviation of 3.594. All participants were paid for their participation and gave written informed consent. All participants had normal or corrected-to-normal vision. We encouraged participants to wear contact lenses for a more comfortable Oculus VR experience. Among all participants, 13 had prior experience with three-dimensional computer games, and 9 had previous experience on VR; 15 had experienced motion sickness of different severity previously in their life.

3.2 Physical Space and Virtual Environment

The physical space of the experimental environment was 3 by 5 meters. In each trial, the user was instructed to walk from point A to point B and back to point A (Figure 2a). Both points A and B were marked with black tape on the ground. The distance between A and B was 4.5 m, which can be covered with-in 8 steps by a 175 cm male adult.

The corresponding virtual space to the lab environment was a virtual street scene. The size of the whole Sydney scene was 100 m by 100 m. The virtual walking took place on a straight street of 70 m long and 5 m wide. Figure 2b shows the side view of the street, and Figure 1 shows the first-person view of the participant while performing the walking task.

3.3 Experiment Design

The experiment used a within-subject design with translational gain as the sole independent variable, with 6 levels $\{1, 2, 4, 6, 8, 10\}$. An informal internal pilot test led to our decision to set $10x$ gain as the upper bound of the experiment. VR engineers on our team, who were used to different redirected walking experiments, all considered the virtual walking experience uncomfortable and unusable at gain levels of 10 and above.

The participants experienced 5 trials per gain level, for a total of 30 trials in increasing order from $1x$ to $10x$ during the experiment session. We chose not to randomize the order of translational gain because we hypothesized that exposure to large translational gain would induce severe VR sickness in some participants and sickness symptoms could potentially persist throughout the entire session. Using a fixed increasing order of translational gain also enabled us to investigate the habituation on the translational gain when the VR users were expecting an amplification of the mapping between the virtual and physical worlds.

At the beginning of each trial, the participant was instructed to move to a virtual manhole on the virtual street (point A in Figure 2) . She was then instructed to walk toward a destination indicated by a red arrow (Figure 1) in the virtual scene and then back to the virtual manhole. As the translational gain increased, the position of the red arrow moved farther away from the starting point (Figure 2b). In the physical world, the participant walked between points A and B (Figure 2a). Physical collision was also implemented in the virtual environment to prevent the unlikely event of the user running into the virtual building.

3.4 Apparatus

Motion Capture System. We used an OptiTrack motion capture system with 12 Flex 13 cameras for full-body tracking. Flex 13 captured information at a rate of 120 frames per second. Participants wore the motion capture suit over their clothing. The OptiTrack Unity Plugin synchronized the motion capture data and the coordinate systems in both the OptiTrack cameras and the Unity3D engine. In this experiment, we used the Baseline + Toe marker skeleton setup with 41 tracked markers in the Motive:Body software from OptiTrack. This setup enabled us to calculate biomechanical measurements, including CoM [9, 26], stepping distance, and cadence.

VR Headset. Oculus VR CV1 headset was used in this experiment. We chose Oculus because of its compatibility with the OptiTrack Flex 13 cameras. The head position of the Oculus VR plug-in in Unity3D was overridden by the tracking information from the OptiTrack system, which enabled a larger walking area.The headset contained a pair of OLED displays that provided 110-degree field-of-view with a resolution of 1080 x 1200 pixels per eye.

3.5 Procedure

Before the experiment started, each participant answered a pre-experiment questionnaire, which was designed to provide an understanding of their level of familiarity with 3D and VR technologies and their experience (if any) with motion sickness. Afterward, the participant first wore the motion capture suit and was instructed to freely walk in our tracking area to confirm that the motion capture cameras could track the full body motion inside the tracking volume. Once the motion capture system was ready, the participant started five baseline walking trials without wearing the VR headset. The participant walked between the two ends of the walking area (i.e., positions A and B in Figure 2a). Afterward, the participant put on the VR headset and was introduced to the virtual environment and the task of starting at the starting point (i.e., a virtual manhole), walking toward the end point (i.e., a red arrow), and finally walking back to the starting point. This walk between starting and end points constituted a single trial. At the end of each trial, a virtual message would indicate the end of the trial, and the participant reported her level of sickness from 1 to 10, where 10 meant the sickness was so severe that the experiment should be terminated immediately .

4 Measurements

- **Between-Trial Questionnaire.** At the end of each trial, we asked the participants to express on a scale from 1 to 10 their feelings of dizziness, discomfort, nausea, fatigue, headache, and eyestrain. We chose these symptoms following previous works [29, 40, 53], which also used a sub-set of symptoms in trials to avoid disrupting the immersion.

- **Post-Experiment Questionnaire.** Upon the completion of the VR session, the participant was asked to complete a full SSQ, followed by a semi-structured post hoc interview session where the researcher encouraged participants to think out loud about their experience and responses to the questionnaire.

- **Center of Mass.** To analyze the change in CoM, we calculated the displacement between the CoM measured during the baseline walking trials without the VR headset and the CoM measured during virtual walking at different TG. We followed the methodologies described by Lafond et al. [26] to calculate CoM. The length of all trials was aligned by MATLAB's Dynamic Time Warping function to facilitate the calculation of average CoM displacement.

- **Gait Parameters.** Step distance was calculated based on the motion of the markers on the participant's feet. Following Hreljac et al. [17], each step was segmented by detecting changes in acceleration direction during walking. More specifically, we used the *findpeaks.m* function from MATLAB. The *MinPeakProminence* parameter was set to 0.01 to remove all the noise peaks, leaving only those peaks that represented a significant movement of the feet.

5 Results

On average, the entire experiment took about 25 minutes per participant. Among the 21 participants, 4 were removed: 2 due to tracking malfunction and 2 to software malfunction during the experiment. Out of the 17 remaining participants, 3 participants terminated the experiment before TG $10x$ due to severe VR sickness symptoms at TG $4x$, $6x$, and $8x$ respectively.

5.1 Questionnaire Responses

Table 1 shows the results of the post-experiment questionnaire. Kennedy et al. [24, 45] suggested a threshold around 18 as an indicator of a problematic level of sickness. Eight out of 17 participants had a total severity (TS) score around or higher than 18, including three who quit the experiment prematurely (marked with an * in Table 1). To further investigate the relationship between VR sickness and gait parameter changes, we categorized those 8 participants with high TS scores into the motion sickness group (MS) and the remaining 13 participants into the no-motion sickness group (No-MS). In

Table 1: Post-experiment SSQ results. Rows with * sign are participants who quit the experiment prematurely. SSQ-N is the nausea score, SSQ-O is the oculomotor score, SSQ-D is the disorientation score, and TS is the total score. Rows with red background color are participants in the MS group and rows with green background color are participants in the No-MS group.

	SSQ-N	SSQ-O	SSQ-D	TS
S1	19.08	7.58	55.68	17.96
S2*	57.24	75.8	83.52	38.44
S3	9.54	0	13.92	4.74
S4	57.24	45.48	111.36	41.92
S5	0	0	0	0
S6	19.08	30.32	0	6
S7	28.62	22.74	27.84	13.48
S8	9.54	0	13.92	4.74
S9	38.16	22.74	125.28	40.66
S10	19.08	22.74	0	5
S11	0	0	0	0
S12	66.78	75.8	180.96	65.62
S13	28.62	7.58	55.68	18.96
S14*	38.16	7.58	97.44	31.18
S15	0	0	0	0
S16*	76.32	90.96	153.12	61.14
S17	28.62	0	41.76	14.22

the following paragraphs, we analyze and report measurements for all participants, the MS group, and the No-MS group.

5.2 Trial Questionnaire Results

Out of the symptoms recorded, only dizziness, discomfort, and nausea were reported by every participant. Only 2 participants reported changes in eyestrain. Four participants reported an increase in fatigue (which they later confirmed was due to wearing the equipment and not because of the interaction with the scenario), and only 3 participants reported head ache (2 of which, again, reported it was due to finding the VR headset uncomfortable and not due to interacting with the scenario). To visualize the between-trial questionnaire results, we averaged the responses from all symptoms at each trial. Those responses were then grouped per TG level for each participant and then averaged with the rest of the participants. Figure 3 shows the resulting values for the overall group, as well as for the MS and No-MS groups.

A Friedman test was used to test for the main effect of TG on the user questionnaire responses. A Wilcoxon Signed-rank test was used as a post hoc test in the case that there was any effect. For the overall data, the results showed that there was a significant effect of TG on the reported between-trial sickness scores (results in Table 2, last column). The post hoc test showed that levels 1, 2, and 4 are significant different from the remaining levels and that level 6 is significant different from level 8. On the separated analysis, for both the MS and No-MS groups, there was a main effect of TG on the reported between-trial sickness scores. The post hoc test showed that for the MS group, all levels of TG were signifncatly different from each other. For the Non-MS group, only level 1 is significantly different from levels 2, 4, 6, and 8.

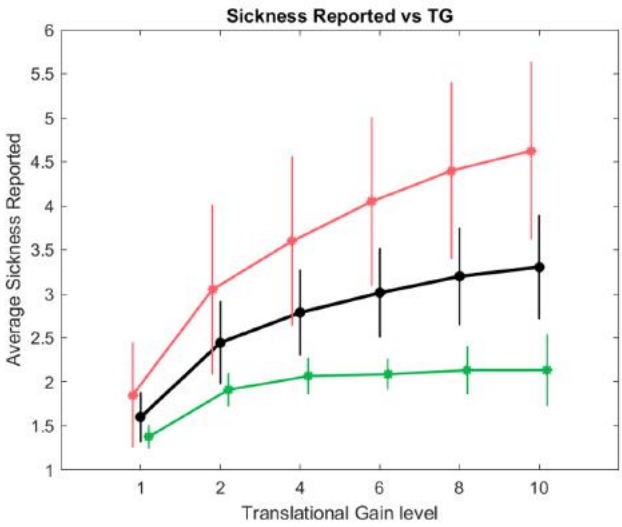

Figure 3: Average per-participant response to each TG level. Black Line: Reported sickness levels at each TG level for all the participants. Red Line: Reported sickness levels at each TG level for participants grouped as MS. Green Line: Reported sickness levels at each TG level for participants grouped as No-MS.

5.3 Behavior and Gait Analysis

The four measurements we analyzed were CoM displacement, stepping distance, cadence, and trial completion time. Figure 4 shows the changes in each of the measurements at the different levels of TG for the all data, MS group, and No-MS group respectively.

The first set of tests compared baseline normal walking without HMD against an isometric virtual walking with $1x$ TG. Normality was tested in the three pairings (cadence, step distance, and trial time completion) using a Shapiro-Wilk test for normality. For the cadence pairing, both data sets did not followed a normal distribution ($W = 0.232, p = 0.032$ for baseline, $W = 0.209, p = 0.002$ for $1x$ TG). For step distance, the pairing followed a normal distribution ($W = 0.187, p = 0.470$ for the baseline recording, $W = 0.086, p = 0.992$ for $1X$ TG). For the trial completion time pairing, both data sets followed a normal distribution ($W = 0.208, p = 0.63$ for the baseline data set, $W = 0.186, p = 0.236$ for TG 1x). For data sets that did not followed a normal distribution, a Friedman test was used to see if there was an effect from walking with the VR headset, while a Wilcoxon Signed-rank test was used as a post hoc in the case that an effect was detected. For data sets that followed a normal distribution, a repeated measure ANOVA with Greenhouse-Geisser correction was used, while a Welch's t test was used as a post hoc. For cadence, we found that an effect existed ($\chi^2(1) = 9.941, p = 0.002$), and the post hoc revealed that there was a difference between the cadences ($Z = -2.959, p = 0.003$). The test on stepping distance revealed that an effect existed ($F(0.274, 0.052) = 79.693, p < 0.05$), and the post hoc revealed that the stepping distances were different ($t(15) = 8.927, p < 0.05$). For trial completion time, there was no effect ($F(1,16) = 2.934, p = 0.106$). This analysis was not done for center of mass, since our data for center of mass already measures a difference between the TG levels and no-VR walking.

The next set of tests compared measurements between different levels of TG. To test for normality, the Shapiro-Wilk test for normality was used. In the case that the data sets followed a normal distribution, a repeated measures ANOVA with a Greenhouse-Geisser correction was used to test for effects, while a Welch's t test was used as a post hoc. For data that does not follow normal distribution, the Friedman test was used as a repeated measure test, and the Wilcoxon

Signed-rank test was used as a post hoc. Table 2 summarizes the results.

5.3.1 Cadence

The first test done to the cadence data was the normality test. On the overall data, only level 10 did not follow a normal distribution ($W = 0.219, p = 0.045$). For the MS group, only level 4 did not follow a normal distribution ($W = 0.375, p = 0.01$). For the No-MS group, levels 1 ($W = 0.18, p = 0.184$), 4 ($W = 0.196, p = 0.46$), and 6 ($W = 0.141, p = 0.712$) followed a normal distribution. The data from the three groups was treated as not following a normal distribution, and the repeated measure tests were used to see if there was any effect of TG levels on the cadence. The results showed that for all the groups there was an effect of TG on cadence ($\chi^2(5) = 33.59, 15.98$ and $21.32, p < 0.05$). The post hoc test on the overall data showed that level 1 differed from the rest of the levels and that level 10 differed from levels 4 and 6. For the MS group, the post hoc test showed that level 1 differed from the rest of the levels and that levels 4 and 6 were different. For the No-MS group, level 1 differed from levels 2, 4, and 6, and level 10 differed from levels 4 and 6.

5.3.2 Center of Mass Displacement

After doing a normality test on the three different groups of center of mass difference, the overall group was treated as not following a normal distribution since level 10 did not follow a normal distribution ($W = 0.214, p = 0.045$). The MS and No-MS groups followed a normal distribution (all TG values had $p > 0.05$). For the overall group, the repeated measure test showed that there was an effect of TG levels on the difference in center of mass. The post hoc test showed that level 1 differed from the rest of the levels, and that level 8 differed from levels 2 and 10. For the MS and No-MS groups, TG level had an effect on the center of mass difference. For the MS group, there was a difference between level 1 and the rest of the levels, and between level 8 and level 10. For the No-MS group, there was a difference between level 1 and levels 4, 6, 8, and 10, and between level 2 and levels 4, 6, and 8.

5.3.3 Step Distance

After running a normality test on the different step distance groups, the results showed that the overall group and the No-MS group followed a normal distribution (all TG values had $p > 0.05$) and that the MS group was treated as not following a normal distribution (level 6 did not follow normal distribution, $W = 0.378, p = 0.041$). For the overall group, the repeated measures test showed that there was an effect from TG on step distance. The post hoc test showed that level 1 differed from levels 4, 6, 8, and 10 and that level 2 differed from levels 6 and 8. For the MS group, the level of TG had an effect on the step distance. The post hoc test showed that there was a difference between levels 1 and 10 and between level 2 and levels 4, 6, 8, and 10. For the No-MS group, there wasn't an effect from TG on the step distance.

5.3.4 Trial Completion Time

For the trial completion time, the overall group of data was treated as not following a normal distribution because levels 1 ($W = 0.234, p = 0.003$), 4 ($W = 0.218, p = 0.003$) and 10 ($W = 0.215, p = 0.015$) did not follow a normal distribution. The MS group followed a normal distribution (all levels had $p > 0.05$). The Non-MS group was treated as not-normally distributed since levels 1 ($W = 0.259, p = 0.043$) and 4 ($W = 0.255, p = 0.017$) did not follow a normal distribution. For the overall and No-MS group, the level of TG had an effect on trial completion time. For the overall group, level 1 differed from the rest of the groups. For the No-MS group, level 1 differed from levels 2, 4, and 6, and level 6 differed from level 10. For the MS, there was no effect from the levels of TG.

6 Interview Responses

All participants except one (S2) reported that the symptoms significantly decreased after removing the headset at the end of the experiment. Out of the 17 participants, 8 participants reported that their level of sickness was partially due to the prolonged use of VR; 3 participants (S3, S9, S10) thought their sickness symptoms were mainly due to the sudden changes of TG across trials. Three participants reported having no symptoms after the experiment finished.

From the pre-experiment interviews, three participants (S2, S14, S16) reported high susceptibility to motion sickness. S2 and S16 stated that as soon as they wore the VR headset, they started to feel very uncomfortable. S2 had to stop the experiment at trial 27 (at the gain level of 8x). S2 was also the only participant whose sickness symptoms did not diminish after removing the headset. S5, S11, and S15 did not report any symptoms after the experiment. S5 stated that she is so used to playing first-person shooting video games online that her experience with constant frame drops in the games prevented her from suffering any symptom. S11 mentioned that she suffers from motion sickness on the bus on a regular basis. However, to her surprise, her VR sickness symptoms subsided once

Table 2: Statistical results for the different measurements. The first 4 columns represent different behavior measurements. The last column represents the sickness level reported by each participant.

	Cadence	CoM Displacement	Step Distance	Trial Completion Time	Reported Sickness Level
Overall	$\chi^2(5) = 33.592$ $p < 0.05$	$\chi^2(5) = 22.98$ $p < 0.05$	$F(2.775, 36.074) = 6.077$ $p = 0.002$	$\chi^2(5) = 22.571$ $p < 0.05$	$\chi^2(5) = 41.274$ $p < 0.05$
	$g\{2,4,6,8,10\} - 1$ $g\{4,6\} - 10$	$g\{2,4,6,8,10\} - 1$ $g\{2,10\} - 8$	$g\{4,6,8,10\} - 1$ $g\{6,8\} - 2$	$g\{2,4,6,8,10\} - 1$	$g\{2,4,6,8,10\}$ - $\{1,2,4\}$ $g\{8\} - 6$
MS Group	$\chi^2(5) = 15.971$ $p < 0.05$	$F(1.826, 7.306) = 6.742$ $p = 0.023$	$\chi^2(5) = 18.029$ $p < 0.05$	$F(1.264, 5.058) = 2.964$ $p = 0.145$	$\chi^2(5) = 37.491$ $p < 0.05$
	$g\{2,4,6,8,10\} - 1$ $g\{6\} - 4$	$g\{2,4,6,8,10\} - 1$ $g\{10\} - 8$	$g\{10\} - 1$ $g\{4,6,8,10\} - 2$	-	$g\{1,2,4,6,8,10\} -$ $g\{2,4,6,8,10\}$
No-MS Group	$\chi^2(5) = 21.317$ $p < 0.05$	$F(2.461, 19.687) = 5.718$ $p = 0.008$	$F(2.44, 19.55) = 2.524$ $p = 0.097$	$\chi^2(5) = 14.651$ $p = 0.012$	$\chi^2(5) = 12.516$ $p = 0.028$
	$g\{2,4,6\} - 1$ $g\{4,6\} - 10$	$g\{4,6,8,10\} - 1$ $g\{4,6,8\} - 2$	-	$g\{2,4,6\} - 1$ $g\{10\} - 6$	$g\{2,4,6,8\} - 1$

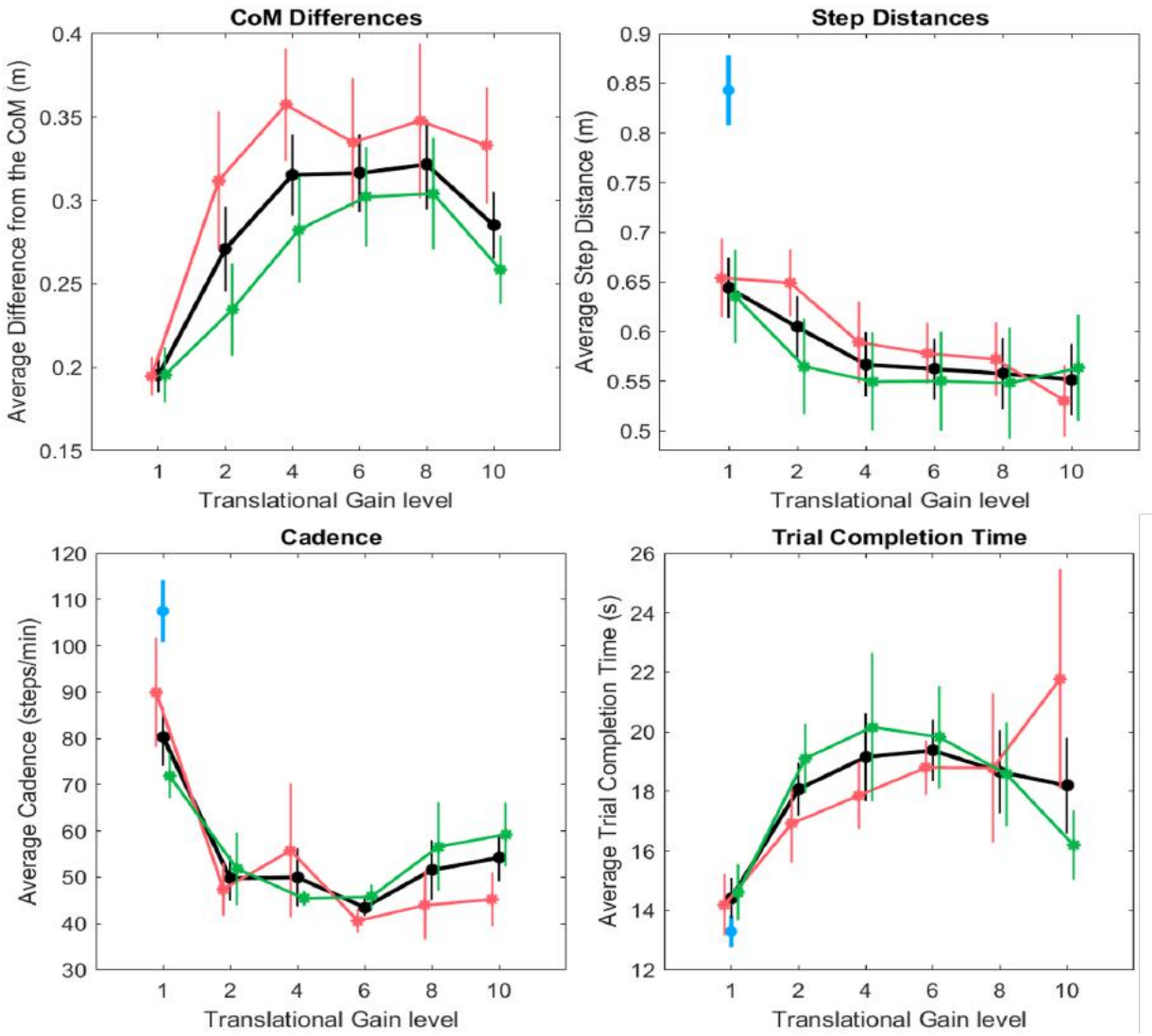

Figure 4: Results of different behavior measurements vs. different levels of TG. Black Line: Average. Red Line: Results from participants belonging to the MS group. Green Line: Results from participants in the No-MS group. Blue Line: Average baseline recording without VR. Position dodge function was used to avoid the overlapping of standard error bars.

she removed the VR headset. S6 also expressed how each change in translational gain caused her surprise and how this surprise caused her to experience vertigo. S16 expressed her difficulty traveling on an airplane, because looking at the movement outside the window while sitting down causes her motion sickness. During the experiment, the participant expressed that after reaching level 2x, she started feeling the same symptoms. This participant dropped out the experiment the earliest, quitting once the gain level changed from 2x to 4x.

Out of the 17 participants, 5 participants (S6, S7, S10, S11, S13) reported that after reaching 15 to 16 trials, they could confidently prepare themselves for the next translational gain change, which helped in decreasing the level of dizziness. Contrary to these statements, 2 participants (S12, S14) expressed that 5 trials were not enough to get used to the translational gain and that the constant change in translational gain caused their symptoms. It is also worth noting that 2 out of the 17 participants (S13, S14) started to feel dizziness and nausea 20 minutes after the experiment ended, although they reported no symptoms at post-experiment SSQ.

7 Discussion

The result showed that TG had main effects on the reported sickness level. In general, as the TG level increased, the reported sickness levels between the trials also increased (Figure 3). However, for the No-MS group, whose participants reported low severity scores in the post-experiment SSQ questionnaires, the between-trials VR sickness scores stayed low even after $2x$ TG and showed no significant difference among the larger TGs $\{2x, 4x, 6x, 8x, 10x\}$. This result seems to suggest that non-isometric virtual walking with a large TG could be an effective and practical navigation method for at least a sub-group of users in the scenario where precise destination selection is not required. Note, one participant reported lower VR sickness at the end of the experiment, possibly because she was better able to adopt to the non-isometric virtual walking or because she was just more resilient to VR sickness in general. Given the fact that none of the participants had ever experienced non-isometric virtual walking before, in this case we would lean toward the latter assumption as being more likely.

We found that gait performance was significantly different be-

tween VR walking and the baseline non-VR walking, which concurred with the findings of Janeh et al. [20, 21]. Among the VR walking trials, the most significant differences in gait performance and CoM displacement were found between the $\{1x\}$ and other TG levels. The difference was particularly prominent when the study participants first experienced an amplified TG at $2x$, as shown in Figure 4. At $2x$ TG, a sudden increase in CoM displacement was revealed, indicating a decrease in posture stability; also, the corresponding gait patterns, namely a significantly smaller stepping distance and slower cadence, were also signs of participants spending more than usual attentional resources trying to to control their gait [54, 55]. These changes also led to a significantly longer trial completion time, despite the physical walking distance for each trial being the same.

At larger TG levels, namely $\{4x, 6x, 8x,$ and $10x\}$, there were few pair-wise significant differences between the measurements. Surprisingly, the participants even on average performed slightly better at large TG $\{8x, 10x\}$ in some measurements, such as demonstrating smaller CoM displacements and a shorter task completion time. The participants in the No-MS group, i.e., those who did not report severe MS symptoms after the experiment, seemed to be able to adapt to the increase of TG particularly well and even started increasing their step distances and thus reducing the task completion time after $4x$ TG. In contrast, participants in the MS group, i.e., those who had reported severe MS symptoms, struggled to perform the virtual walking task as the TG was increased. With the latter group, all their performance measurements steadily decreased, even though at this stage the participants had more experience with non-isometric virtual walking. The discomfort from their MS and other MS symptoms seemed to impede their ability to learn and adapt to virtual walking at larger TG levels.

In summary, non-isometric virtual walking with a large and detectable TG is a simple and straight-forward navigation technique that can be used to expand the coverage of a virtual environment within a restricted physical space. All the present study participants understood the concept quickly and could use the technique without any prior training. However, this navigation technique might not be suitable for all users. Even with a clear expectation of a large visual motion and with repeated exposure to the virtual walking experience, some users might still experience severe VR sickness symptoms and may not be able to adapt to larger TGs. Understanding how to predict users' resilience to the effects of virtual walking with different TGs will be an important step toward promoting non-isometric virtual walking with large gains as a practical navigation method in the virtual environment.

8 Future Works

The presented experiment design used a single independent variable of translational gain. It would be interesting to investigate whether the results could be generalized for other types of redirected walking techniques, such as rotational and curvature gain. Previous works [16, 46] found that users are more sensitive to translational gain than rotational gain, and so it would be interesting to test this statement at larger gain values and for people with different susceptibility to VR sickness.

Previous works reported that visualization of a virtual avatar would affect the level of a user's presence and induce different responses toward visual stimuli in the virtual environment [4, 41, 42]. However, we opted not to show the virtual avatars because of the challenges involved in visualizing the locomotion animation correctly with the increase in the translational gain. At larger TG, an accelerated animation would create an illusion of sliding on the floor. To avoid the risk of this confounding our participants, we decided to hide the avatar. Nevertheless, we believe it is an interesting research question and future studies should investigate how to visualize the walking animation correctly when using an amplified translational gain.

9 Conclusion

This paper presents the findings from an experiment investigating VR sickness and gait parameters during non-isometric virtual walking with large and perceivable translational gain. Most participants could accomplish the non-isometric virtual walking, even with large gains and without any prior training. However, overall, as the TG increased, participants reported higher VR sickness scores during the experiment. Changes in gait performance and CoM displacement were most prominent when the participants first experienced amplified virtual walking at $2x$ TG. However, the gait performance seemed to stabilize and remain relatively stable after $2X$ TG and there were few significant differences detected among higher TGs $\{4x, 6x, 8x, 10x\}$. Surprisingly, participants with lower post-experiment SSQ scores adopted to the virtual walking with large TGs very well and even started showing gait performance improvement, even at large translational gain levels.

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