The Role of Binocular Vision in Avoiding Virtual Obstacles While Walking

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Abstract—Advances in Virtual Reality technology have enabled physical walking in virtual environments. While most Virtual Reality systems render stereoscopic images to users, the implication of binocular viewing with respect to the performance of human walking in virtual environments remains largely unknown. In the present study, we conducted two walking experiments in virtual environments using a linear treadmill and a novel projected display known as the Wide Immersive Stereo Environment (WISE) to study the role of binocular viewing in virtual locomotion. The first experiment investigated the walking performance of people stepping over obstacles while the second experiment focused on a scenario on stepping over gaps. Both experiments were conducted under both stereoscopic viewing and non-stereoscopic viewing conditions. By analysing the gait parameters, we found that binocular viewing helped people to make more accurate movements to step over obstacles and gaps in virtual locomotion.

Index Terms—Stereopsis, Virtual Locomotion, Virtual Environments.

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1 INTRODUCTION

VIRTUAL Reality (VR) systems often provide people with opportunities to walk physically in virtual environments with their legs. While most present-day VR systems (including VR locomotion systems) provide stereoscopic viewing to users, little is known about the relationship between stereoscopic viewing and users' walking performance in virtual environments. As rendering stereoscopic images requires additional computational resources and the benefits to render stereoscopic image in such scenarios are largely uncertain, it is necessary to investigate the effects of stereoscopic rendering and viewing on the performance of human walking in virtual environments.

Virtual locomotion techniques are divided into three categories [1]: Walking-in-Place [2] [3] [4] [5] [6] [7] [8] [9] [10] [11], Redirected Walking [12] [13] and mechanical repositioning (to reposition a user to the center of the tracked physical space using mechanical devices, such as treadmills [14], foot platforms [15], pedalling devices [16] and spheres [17], *etc.*). In the current paper, we focused on the mechanical repositioning techniques to conduct our study. VR displays combined with mechanical repositioning techniques provide us with a unique opportunity to simulate large open environments. These systems enable people to walk over long distances with their motion recorded in a limited physical space. Thus, these are promising platforms to investigate the influence of stereoscopic rendering and viewing on gait parameters during continuous walking in virtual environments. Compared to Walking-in-Place techniques, mechanical repositioning enables forward-backward leg swing motion during walking and is thus more suited to our investigation on stepping over movements in virtual environments. Redirected Walking techniques introduce an additional turning factor compared to Walking-in-Place and mechanical repositioning using a 1-D treadmill. The present study focused on linear walking based on a 1-D treadmill and we plan to investigate the role of stereoscopic rendering and viewing in Redirected Walking techniques in future studies.

In the current study, we presented two experiments in VR to examine the effects of stepping over obstacles and gaps during linear continuous walking under stereoscopic and non-stereoscopic viewing conditions. Stepping over obstacles and gaps was interesting to us to study as people often encounter them during walking. Gaps are particularly of interest as they may not look obvious when viewed at a distance. While the walker must clear the extent of the gap, toe clearance is not an issue. It is interesting to investigate whether stereoscopic viewing makes a difference in this case. These experiments were conducted using a novel immersive projected display, known as the Wide-Field Immersive Stereoscopic Environment (WISE, see Figure 2 below). This display has been set up at York University to investigate human locomotion and navigation behaviours as well as to develop interaction techniques with large-scale projective displays in VR environments. This display together with a 1-D treadmill allowed us to implement straight line walking in VR. Virtual scenes that presented obstacles and gaps for the experiments based on the setup were designed.

The main contributions of the paper are two-fold:

(1) We present a method and experiment designs for studying human walking performance in virtual environments based on a projective display and a linear treadmill.

(2) We show that stereoscopic rendering and viewing enable more accurate movements to step over obstacles and gaps in virtual environments during continuous walking.

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Manuscript received April x, 20xx.

2 RELATED WORK

Stereopsis (stereoscopic vision) is important for visually guided behaviour and has been shown to aid hand-eye coordination [18]. Many studies have been conducted to study the relationship between stereoscopic vision and the performance of tasks related to upper limbs. Stereoscopic vision was originally considered to be not very helpful for locomotion, as a period of steady viewing is required for maximum precision [19]. However, more recent studies have shown that stereoscopic viewing provides advantages over non-stereoscopic viewing in terms of more accurate lower limb movements.

Patla *et al.* [20] conducted an experiment to study the role of stereopsis in locomotion by asking participants to step over a single obstacle along a straight path. Their finding was that toe clearance was increased under non-stereoscopic viewing compared to stereoscopic viewing, which indicated that stereoscopic viewing improved lower-limb lift accuracy or that people acted more cautiously in absence of stereoscopic viewing.

Loomis *et al.* [21] had participants to go through a small field with randomly placed obstacles to reach a goal at the other end of the field, while avoiding collision with the obstacles. Results showed that stereoscopic viewing resulted in fewer collisions compared to non-stereoscopic viewing.

Hayhoe *et al.* [22] studied the role of stereopsis in locomotion by asking participants to walk in an indoor environment with two obstacles and one table. The task was to step over two given obstacles, go around the table and step over the two obstacles again before returning to the start point. They found that stereoscopic viewing gave shorter task completion time and lowered foot clearance height compared to non-stereoscopic viewing. The finding on the foot clearance (toe clearance) height was consistent with that of Patla *et al* [20].

Chapman *et al.* [23] investigated the influence of stereopsis in foot placement accuracy using a task that asked participants to walk in a straight path and step on floor targets as accurately as possible. Each floor target consisted of two pieces of white tape angled 90 degrees to form to a corner of a square. They found that, under the non-stereoscopic viewing condition, foot placement was less accurate in medio-lateral plane and terminal foot-reach duration was longer compared to that of stereoscopic viewing.

Although these studies have been conducted, there are two questions that are yet to be answered. First, by common knowledge, people tend to walk cautiously in limited space when a few obstacles were presented. It is uncertain whether the results still apply as they are adjusting an ongoing relatively automatic motor action during continuous walking. Second, in virtual environments, due to the introduction of VR displays and mechanical repositioning devices, the walking dynamics of people changes compared to normal overground walking [24] and the perception of walking speed also differs [25]. In such cases, it is not certain that stereoscopic viewing will allow for more accurate movements.

More recently, Matthis *et al.* [26] studied the relationship between gaze and control of foot placement in natural environments. Binaee and Diaz [27] introduced an augmented reality apparatus to investigate whether such devices are suitable for studying the control of gait in relation to vision. Barton *et al.* [28] studied walking behaviours of people when perturbation is introduced during forward walking to step over obstacles. Srivastava *et al.* [29] reviewed the correlation between saccades and locomotion. However, to the authors' knowledge, no study has been conducted to investigate the relationship between stereoscopic viewing and gait during continuous walking in virtual environments.

3 METHODS

3.1 Hardware and Software of the VR system

The virtual environments for the experiments were presented on the large-scale curved projected display – the WISE. The images rendered on the display were cast and seamlessly merged by eight stereoscopic overlapping projectors, with blending and luminance calibration performed in hardware. Each projector was driven by a client machine (HP Z820 Workstation with nVidia Quadro k5000 graphics card) in a real-time rendering cluster. The rendering and the synchronization between the host machine (HP Z820 Workstation with nVidia Quadro k5000 graphics card) and the client machines were handled by the VR software Worldviz Vizard 5.7. Stereoscopic viewing was presented through the Christie shutter glasses at a refresh rate of 60 Hz for each eye. The Worldviz PPT Eyes tracker was mounted on the top of the glasses frame to track head movements. Body movements of participants, including head motion and foot motion, were captured using the Worldviz PPT system, which used infrared (IR) cameras to capture IR light emitted by markers attached on body parts to be tracked. Three IR cameras were mounted on the top of the display facing the ground to track head positions while another three IR cameras were mounted under the display facing the treadmill to track foot positions. The 3-D positions of the tracked IR markers were calculated by the Worldviz PPT Studio and was shared with the Worldviz Vizard simulation through the Virtual-Reality Peripheral Network (VRPN) [30]. The PPT Eyes were equipped with two IR markers mounted on the top of the glasses frame. This enabled the 3-D position and orientation of the PPT Eyes (i.e. the position and the orientation of the head) to be tracked. Disparity between eyes and perspective transformation of a scene were generated based on tracked head position in real-time. A commercial 1-D treadmill, LifeSpan TR5000-DT5, was used as the walking platform. The top surface of the treadmill belt had a size of 51 cm (W) × 142 cm (L). The treadmill was controlled through Universal Asynchronous Receiver/Transmitter (UART) controllers by a host machine using a baudrate of 4800 bit/s. The speed of the treadmill was queried periodically at a frequency of 5 Hz. The queried value was synchronized to the speed of the virtual viewpoint to create egocentric motion in virtual environments. The position of the virtual viewpoint and the positions of tracked body parts were recorded at a frequency of 60 Hz. The experimental software application that integrated the presentation of virtual environments, hardware control and data recording was implemented using Python 2.7. This integrated VR system allows participants to perform linear walking with their movements recorded.

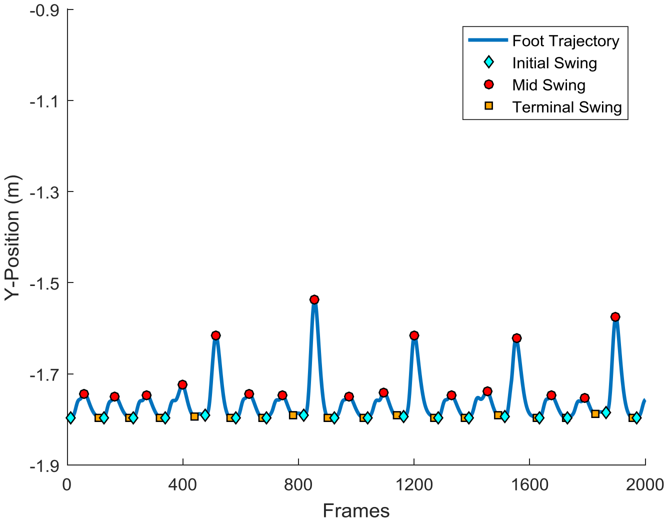

Fig. 1: Exemplar segmentation of gait cycles performed on low-pass filtered data frames (y-axis showed the actual physical values of tracked y-positions of foot movement relative to the zero plane in tracked physical space).

3.2 Feature Extraction for Gait Analysis

Recorded foot positions from the IR markers mounted on participants' ankles were used for data analysis. Estimated gait parameters extracted from tracked foot positions were used to study how stereopsis affects people's walking performance. We explain our method for extracting gait parameters of walking on a treadmill in this section.

The position of a tracked foot is denoted as a 3-D vector $p_f = (x_f, y_f, z_f)$, where x_f, y_f and z_f are lateral, vertical and depth positions, respectively. A sequence of recorded foot positions is represented as $P_f = p_{f1}p_{f2}...p_{fi}$, where i is the index for a 3-D vector p_f. Contrary to over-ground walking in which the z-position of a person's foot monotonically increases or decreases, when a person walks on a treadmill their feet perform reciprocating motion in terms of depth and the tracked z-position oscillates as opposed to over-ground walking. As we aim to analyse participants' gait in virtual environments, it is necessary to match the tracked physical foot position to the equivalent virtual foot position in the virtual environment. This can be done by performing a transformation on the tracked physical foot position with respect to the position of the virtual viewpoint, which is represented as p_v. A sequence of positions of virtual viewpoint is represented as $P_v = p_{v1}p_{v2}...p_{vi}$. Recall that we synchronized the speed of the virtual viewpoint with respect to the speed of the treadmill. Assume that a person walks on the treadmill with their head position maintained at the center of the treadmill and tracked in physical space, their head position in the virtual environment is essentially the position of the virtual viewpoint p_v as the person walks forward. As the changes of foot positions are relative to the head position in tracked physical space, the transformation between foot positions in tracked physical space and in the virtual environment can be performed by adding the sequence of the foot positions P_f and the sequence of the positions of virtual viewpoint P_v. The x-component and y-component in p_v were set to zero for transformation, with $p_{vi} = (0, 0, z_{vi})$, since it was not necessary to transform the x-component and y-component of P_f and we only needed to recover the depth of P_f. This gives:

$$P_t = P_f + P_v$$

where P_t is the transformed foot position sequence with $P_t = p_{t1}p_{t2}...p_{ti}$ and $p_{ti} = (x_{ti}, y_{ti}, z_{ti})$. After the transformation, foot velocity V_t was calculated from P_t. P_t and V_t were smoothed using 2nd order Butterworth filters with a cut-off frequency of 1 Hz to remove noise. The transformation and filtering were performed on recorded position data of both feet.

A gait cycle is defined as two consecutive heel strikes of the same foot [31]. To extract gait cycles for analysis, we examined the sequence of transformed vertical foot positions y_{ti}. This is similar to the approach presented in [32] that used foot speed in depth to segment steps. Specifically, we located local minimums between peaks to segment a gait cycle by first applying a high threshold τ_h to the data sequence of y_{ti} (the median of the data sequence of y_{ti} was set as τ_h). From the thresholded data points, the algorithm used gradient descent to locate the initial swing s_{init} and the terminal swing s_{term} (which correspond to frames). The gradient descent stopped whenever it reached the minimum threshold τ_l or it found that the gradient was ascending, indicating a different gait cycle was detected. Once the initial swing s_{init} and the terminal swing s_{term} were successfully located, the maximum position value in the interval between these two swing points was selected and its index was considered as the mid swing s_{mid}. Figure 1 shows an example of segmented gait cycles on a single foot trajectory that stepped over obstacles. This approach was in general more robust than applying a single threshold to segment gait cycles. With the detected initial swing s_{init}, mid swing s_{mid} and terminal swing s_{term}, it was easy to calculate gait parameters, such as stride length and stride height. We then merged the gait cycles segmented from the position data of both feet based on the sorted z-position of the mid swing s_{mid} of the gait cycles to obtain a single sequence of gait cycles in an ascending order of z-positions.

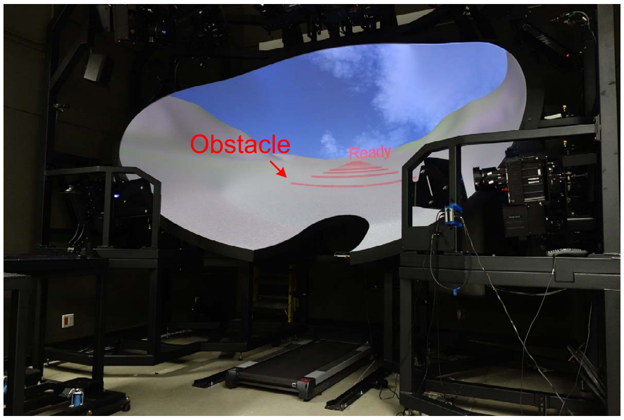

Fig. 2: The setup of experiment 1.

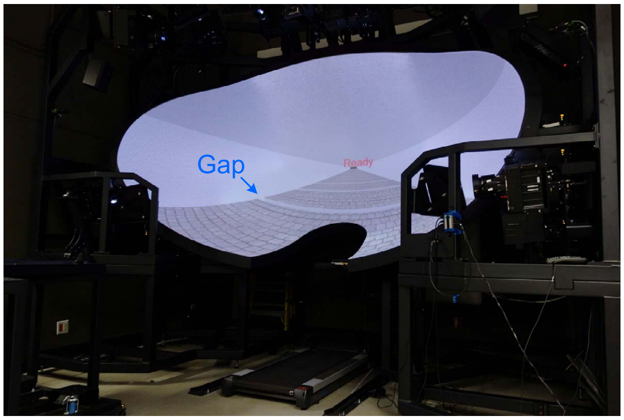

Fig. 4: The setup of experiment 2.

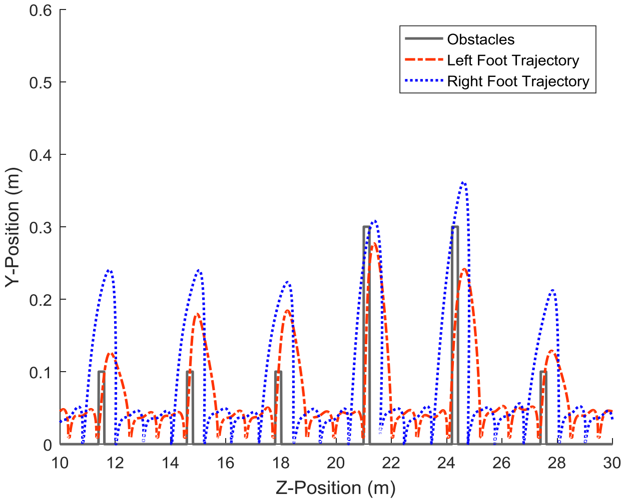

Fig. 6: Foot trajectories on stepping over obstacles (representative data captured from a participant in stereoscopic viewing condition).

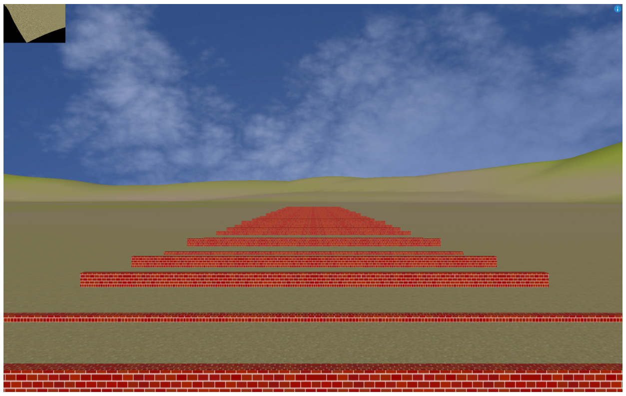

Fig. 3: Console view of experiment 1 (the inset image is for monitoring the various projectors and was not seen in the experimental display).

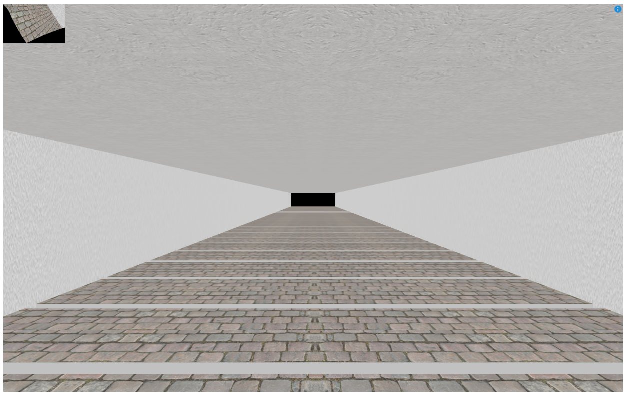

Fig. 5: Console view of experiment 2 (the inset image is for monitoring the various projectors and was not seen in the experimental display).

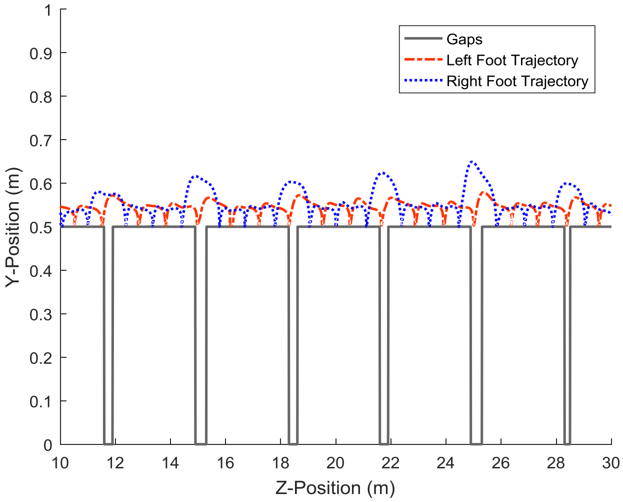

Fig. 7: Foot trajectories on stepping over gaps (representative data captured from a participant in stereoscopic viewing condition).

Distinguishing foot position data between left foot and right foot was not necessary for further data analysis.

We used the minimum distance classifier [33] to register the merged gait cycles with respect to obstacles or gaps presented in experiments. In other words, the responses (gait cycles) were associated with stimuli (obstacles with different heights or gaps with different depths) through the classification. This was done by calculating the Euclidean distances between the z-position of the mid swing s_{mid} of the merged gait cycles G_j and the centres of the z-position of obstacles or gaps C_i:

$$R_i = \operatorname*{argmin}_i \|G_j - C_i\|_2$$

where j is the index of the z-position of the mid swing s_{mid} of the merged gait cycles G_j and i is the index of the centres of the z-position of obstacles or gaps C_i, respectively. R_i is the resulting index of an obstacle or gap to be associated with its corresponding gait cycles G_j. In practice, this equation was solved by looping through all combinations of z-positions of gait cycles and z-positions of obstacles or gaps. The pairs with the minimum Euclidean distance were registered together. When the registration was completed, we were able to evaluate a specific gait cycle with respect to the obstacle or the gap that it covered. We defined the following metrics to evaluate the gait performance of participants:

- **Stride length** l_s:
  the z-distance between initial swing, s_{init}, and terminal swing, s_{term}.
- **Stride height** h_s:
  the difference in height of the foot at mid swing, s_{mid}, and when the foot was planted (the average of y-positions of initial swing s_{init} and terminal swing s_{term}).
- **Foot lifting distance to obstacles or gaps** d_l:
  the difference in z-distance of the foot at initial swing, s_{init}, and the front face of an obstacle or the front edge of a gap.
- **Foot planting distance to obstacles or gaps** d_p:
  the z-distance between the foot at terminal swing, s_{term}, and the back face of an obstacle or the back edge of a gap.
- **Foot clearance to obstacles** d_c:
  the y-distance of mid swing, s_{mid}, to the top of an obstacle. Foot clearance to gaps were not assessed as this is the same parameter as stride height h_s, with an added deepness of gaps fixed as 0.5 m.
- **Foot speed of mid swing** s_f:
  the instantaneous speed of mid swing, s_{mid}, obtained by calculating the Euclidean norm of the y-component and the z-component of foot velocity V_t.
- **Number of strides** n_s:
  the number of strides that were taken during a single walking trial.
- **Number of collisions** n_c:
  the number of collisions happened between the transformed foot position P_t and the bounding boxes of obstacles or gaps during a single walking trial. As people were unable to step into a gap physically, the bounding boxes of a gap was modeled with a low height of 0.01 m above the ground surface to determine the occurrence of collisions.

4 EXPERIMENT 1: STEPPING OVER OBSTACLES

4.1 Introduction

The goal of the experiment was to investigate whether stereoscopic viewing provides advantages when people step over obstacles.

4.2 Design

In this experiment, we designed an outdoor environment that had a valley and a skydome, using Autodesk 3ds Max 2016, shown in Figure 2. A console view of the scene on the host machine is shown in Figure 3. The texture for the valley was manually blended from a grass texture and a gravel texture while the texture for the skydome was a high definition picture that captured a bright sky with few white clouds. The obstacles were brick-textured cubic objects. The width (x-axis) and depth (z-axis) of the obstacles were fixed as 10 m and 0.2 m, respectively. The heights (y-axis) of these obstacles had three different values, which were 0.1 m, 0.2 m and 0.3 m. Each of these three different conditions was repeated ten times. Thus, in total, there were thirty obstacles in an experimental scene, with the order of the obstacles randomized. The distance between the participant to the front face of the first obstacle was 5 m. The distance between the back face of an obstacle and the front face of its immediate successive obstacle was 3 m. This gave participants an adequate amount of distance to walk normally and adjust their footsteps before stepping over the next obstacle. The total length of each walking path was approximately 100 m. Participants were expected to perform constant speed linear walking in the virtual environment.

Each walk through an experimental scene with a random order of generated obstacles was considered as a single trial. Participants were first asked to perform two trials under the stereoscopic viewing condition as practice to get familiar with the hardware and the virtual environment. Then, participants were asked to perform two trials under stereoscopic viewing condition and two trials under non-stereoscopic viewing condition. The order of trials in stereoscopic viewing condition and non-stereoscopic viewing condition were counter-balanced to control for order effects. Five participants followed an order of viewing conditions of SSNN, where S denotes the stereoscopic viewing condition and N denotes the non-stereoscopic viewing condition while another five participants followed an order of NNSS. For the non-stereoscopic viewing condition, participants were also asked to wear the PPT Eyes, but modeled distance between two eyes was set to zero.

4.3 Participants

Ten people (7 males, 3 females, age: 24 - 39, height: 1.59 - 1.90 m) participated in the experiment. All had normal or corrected-to-normal vision. Stereo acuity of participants was verified using the Randot Stereotest (Stereo Optical Company, Inc. Chicago IL). All had good stereo acuity ($\leqslant$ 50 seconds of arc). Informed consent was obtained from

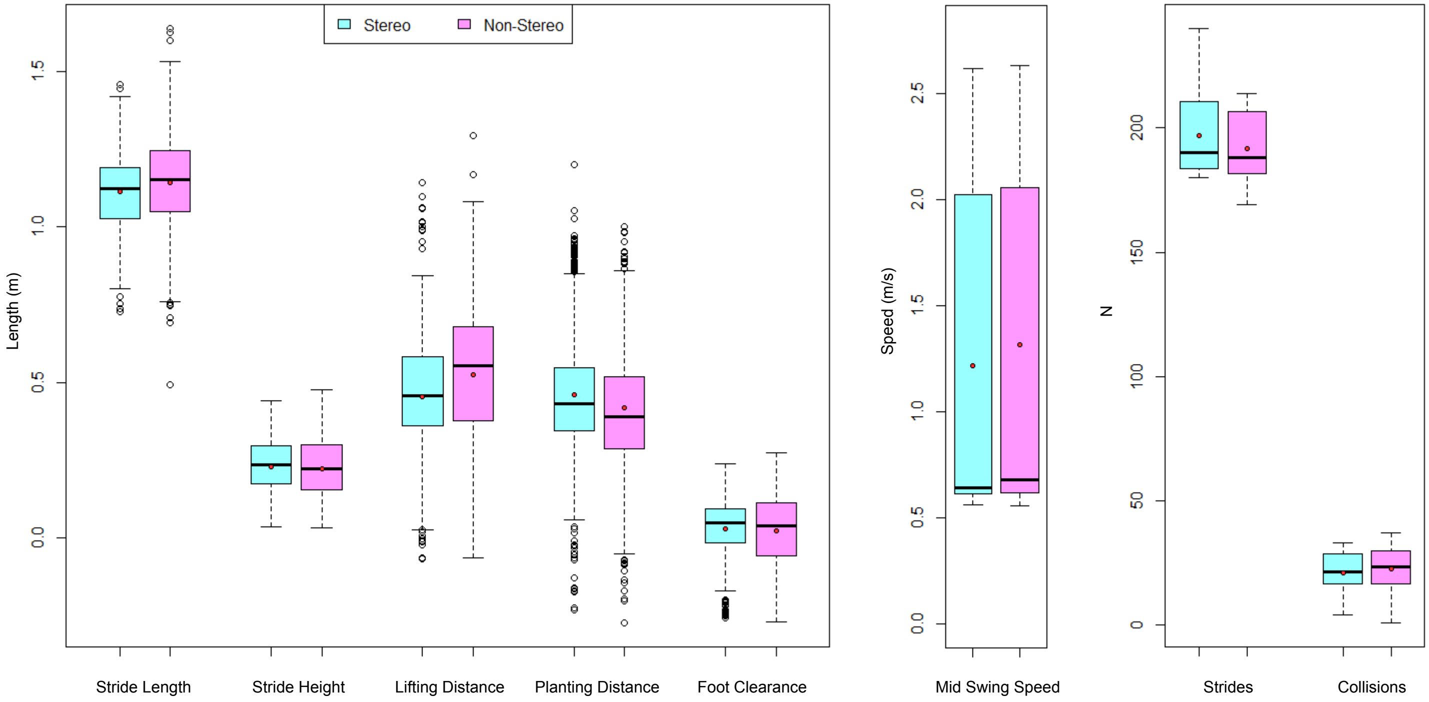

Fig. 8: Gait parameters on stepping over obstacles by viewing condition (red dots denote mean values; the boxes of the number of strides and the number of collisions denote the data distribution of that of all walking trials of each viewing condition across participants; for other gait parameters, the boxes denote the data distribution from the gait parameters of all gait cycles that covered an obstacle for each viewing condition. Box plot convention: whiskers denote maximum and minimum, top and bottom of a box denote upper quartile and lower quartile and the line in a box denotes median).

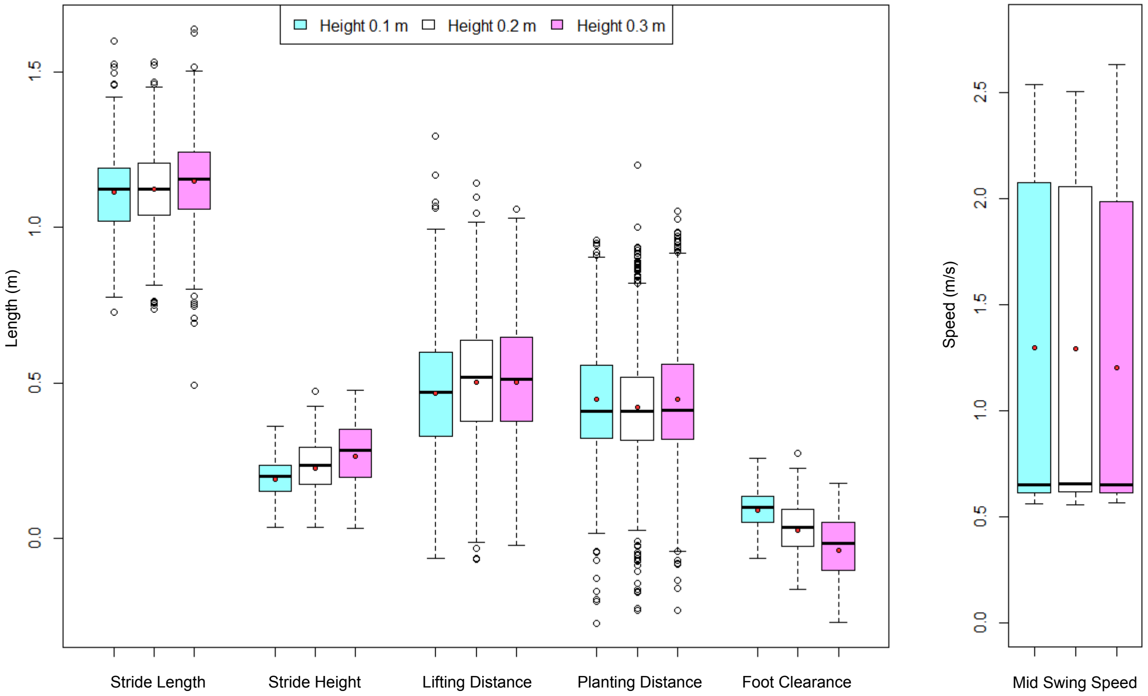

Fig. 9: Gait parameters on stepping over obstacles by height level (red dots denote mean values; the boxes of these gait parameters denote the data distribution from the gait parameters of all gait cycles that covered an obstacle for each level of obstacle height. Box plot convention is as in Figure 8).

TABLE 1: Results of the Linear Mixed-Effects Models analyses on stepping over obstacles

		l_s	h_s	d_l	d_p	d_c	s_f
Viewing Condition	$F(1, 1185)$	18.99	0.98	38.19	14.00	0.98	5.66
	p	**<0.001**	0.322	**<0.001**	**<0.001**	0.322	**0.017**
	η_p^2	0.016	0.001	0.031	0.012	0.001	0.005
Height Level	$F(2, 1185)$	9.19	111.58	3.73	2.39	325.68	2.29
	p	**<0.001**	**<0.001**	**0.024**	0.092	**<0.001**	0.102
	η_p^2	0.015	0.158	0.006	0.004	0.355	0.004
Viewing Condition × Height Level	$F(2, 1185)$	0.04	5.81	1.35	1.25	5.81	0.91
	p	0.964	**0.003**	0.258	0.288	**0.003**	0.401
	η_p^2	0.000	0.010	0.002	0.002	0.010	0.002

		n_s	n_c
Viewing Condition	$F(1, 29)$	5.99	0.81
	p	**0.021**	0.376
	η_p^2	0.171	0.027

Note: Significant p-values ($p \leqslant 0.05$) are in bold.

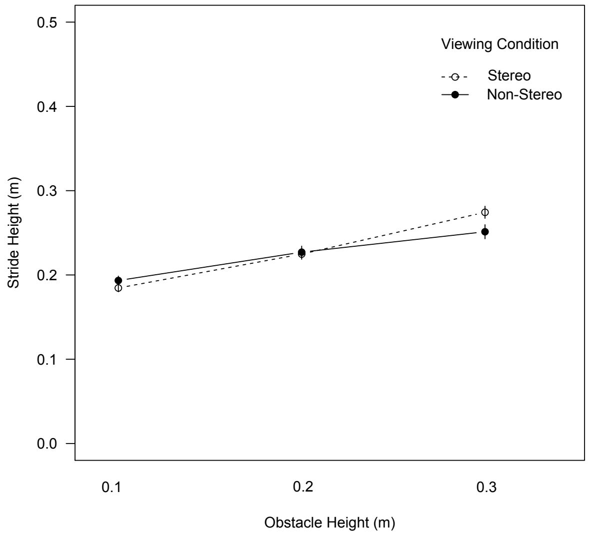

Fig. 10: Interaction effect on stride height (error bars denote the standard error of the mean).

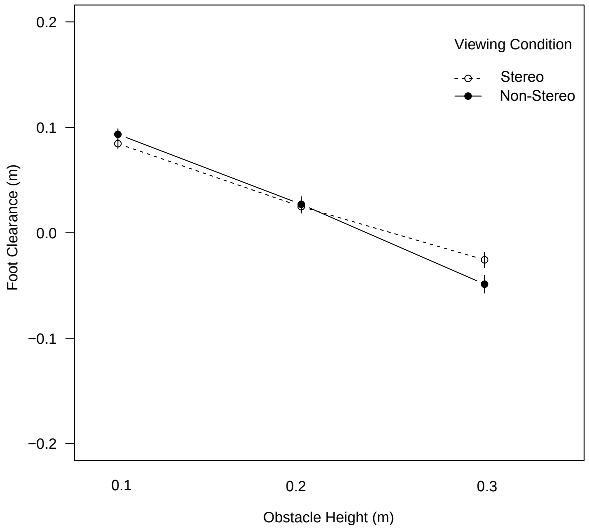

Fig. 11: Interaction effect on foot clearance (error bars denote the standard error of the mean).

all participants in accordance with a protocol approved by the Human Participants Review Subcommittee at York University.

4.4 Procedure

During experimental sessions, participants wore the PPT Eyes on their head and two IR markers on their two respective ankles and stood on the treadmill. For a single experimental trial, when the experiment was started, a ten-second countdown timer was shown on the WISE and the data collection started at the same time. The belt of the treadmill automatically began to move when the timer counted to zero. Then, the treadmill accelerated to 2 km/h and maintained this speed through an experimental trial. Participants were asked to accommodate their walking speed to the speed of the treadmill and step over obstacles when they felt necessary. When the virtual viewpoint passed the last obstacle in the virtual scene, another three-second countdown timer was shown on the WISE, informing participants that the experiment would finish soon. The experiment ended when the timer counted to zero, with the data collection and treadmill stopped simultaneously.

4.5 Results and Discussion

A segment of recorded foot trajectories when stepping over obstacles can be seen in Figure 6 for illustration. To analyse the experimental data, we applied the method described in Section 3.2 on recorded foot positions to extract gait parameters using Matlab 2016a. We then performed statistical analysis on the extracted gait parameters defined in Section 3.2 using R 3.4.2. The Linear Mixed-Effects Models analyses (package NLME in R) were used to study the effects of the experiment. Inter-subject variability was automatically accounted for in the model by treating participants as a random effect. Effect sizes were reported using partial eta squared η_p^2 (estimated from repeated-measures ANOVA analyses of the same form as the Linear Mixed-Effects Models analyses). The independent factors involved were viewing conditions (stereoscopic and non-stereoscopic) and height levels (0.1 m, 0.2 m and 0.3 m) of the obstacles while the dependent factors were the gait parameters. Obstacle height and viewing conditions were treated as fixed effects and participants were treated as a random effect. We included an interaction term between obstacle height and viewing conditions to examine whether the effect of viewing conditions on gait is dependent on obstacle height. Post-hoc pairwise comparisons were performed using Tukey's range tests. Figure 8 and Figure 9 show box plots on gait parameters and Table 1 summarizes the results of the Linear Mixed-Effects Models analyses. Although we had only ten participants, we actually had 1200 data samples for the experiment - each participant walked for two trials under stereoscopic viewing and two trials under non-stereoscopic viewing, and in each walking trial, there were thirty obstacles that they needed to step over. The movement to step over an obstacle was considered as an individual movement trial. Hence, we obtained 1200 repeated measures data samples.

Viewing conditions significantly affected stride length l_s ($p < 0.001$), foot lifting distance to obstacles d_l ($p < 0.001$), foot planting distance to obstacles d_p ($p < 0.001$) and mid swing speed s_f ($p = 0.017$). Stride length under stereoscopic viewing was smaller than for the non-stereoscopic viewing condition. Stride length under stereoscopic viewing was more accurate as a smaller stride was sufficient to cover an obstacle. In Figure 8, we found that the mean value of the foot lifting distance to obstacles d_l was smaller under stereoscopic viewing condition than non-stereoscopic viewing condition. We also found that the mean value of the foot planting distance to obstacles d_p was larger under stereoscopic viewing condition than non-stereoscopic viewing condition. The result showed stereoscopic viewing was beneficial as, logically, if we wish to safely step over an obstacle, we could step as closely to the front side of the obstacle as possible with one foot and walk over it with the other foot to plant far from the back side of the obstacle. It was obvious that stereoscopic viewing helped to realize this aim during walking. The mean value of mid swing speed was lower under stereoscopic condition than non-stereoscopic condition.

Although there was no significant effect of viewing condition alone on stride height h_s, there was a significant interaction effect between viewing conditions and height levels on stride height h_s ($p = 0.003$) (Figure 10, which was consistent with the significant interaction effect between these factors on foot clearance to obstacles d_c ($p = 0.003$) (Figure 11). But the interaction effects on both parameters were weak. For both stride height h_s and foot clearance to obstacles d_c, Tukey's range tests showed that there was a significant difference between stereoscopic viewing *vs* non-stereoscopic viewing on height level 0.3 m but not for height levels 0.1 m and 0.2 m. The mean value of the stride height h_s for obstacles with a height of 0.3 m under stereoscopic viewing was 0.27 m while the mean value under non-stereoscopic viewing was 0.25 m, which showed that people tended to lift their feet higher under the stereoscopic viewing condition when they encountered obstacles with a height of 0.3 m. This may imply that users were better able to execute the task of clearing the virtual obstacle when walking with stereoscopic vision as their feet were lifted higher on average. Similarly, we also found that the mean value of foot clearance to obstacles under stereoscopic viewing was higher than non-stereoscopic viewing. However, there were no interaction effects on other gait parameters. The mean value of stride height h_s under both stereoscopic viewing and the non-stereoscopic viewing was generally insufficient for stepping over obstacles. This may reflect that in virtual environments, there was no actual tripping consequence when the stride height was lower than the height of obstacles. Alternatively, when walking on a moving treadmill in a virtual environment, people may have acted more cautiously to maintain their balance. Thus, their feet were not lifted high enough for the obstacles with a height of 0.3 m.

A significant effect was found on number of strides n_s between viewing conditions ($p = 0.021$). Walking under stereoscopic viewing resulted in more strides compared to non-stereoscopic viewing (Figure 8). Given that the total lengths of walking paths for all experimental trials were nearly the same, it suggested that the cadence under stereoscopic viewing was higher than non-stereoscopic viewing. This was also confirmed by shorter stride length in stereoscopic viewing compared to non-stereoscopic viewing. In addition, there was no significant effect on number of collisions n_c ($p = 0.376$), which suggested that avoiding collision with obstacles was equally difficult between stereoscopic viewing and non-stereoscopic viewing in virtual environments.

Obstacle height significantly affected stride length l_s ($p < 0.001$), stride height h_s ($p < 0.001$), foot lifting distance to obstacles d_l ($p = 0.024$), foot clearance to obstacles d_c ($p < 0.001$) but did not affect foot planting distances to obstacles d_p ($p = 0.092$) and mid swing speed s_f ($p = 0.102$). In Figure 9, we found that for obstacles with a height of 0.3 m, participants' feet were not lifted high enough as the mean value of foot clearance was clearly negative. Tukey's range tests revealed that there were significant differences between three different height levels on stride height h_s and foot clearance to obstacles d_c; a significant difference between height level 0.1 m and height level 0.3 m on stride length l_s; and significant differences between height level 0.1 m and height level 0.2 m and between height level 0.1 m and height level 0.3 m on foot lifting distance to obstacles d_l. Thus, people adjusted their footsteps when they encountered obstacles with different heights.

In Figure 8 and Figure 9, we noticed there were some outliers. A probable reason for these outliers was that people failed to make proper movements to step over an obstacle, even though they had two training trials before. When this happened, the trajectory of a stride might not cover the obstacle but the algorithm would still register the stride to the centre of the nearest obstacle in depth, which resulted in the outliers in these figures. To assess the potential impact of these trials we removed these potential outliers from the dataset and ran the analyses again. We confirmed that the pattern of significant results and in particular our finding that participants failed to lift their feet sufficiently to clear the obstacle still held.

4.6 Summary of the Results

Experiment 1 found that stereoscopic viewing enabled more accurate movements to step over obstacles. This was con-

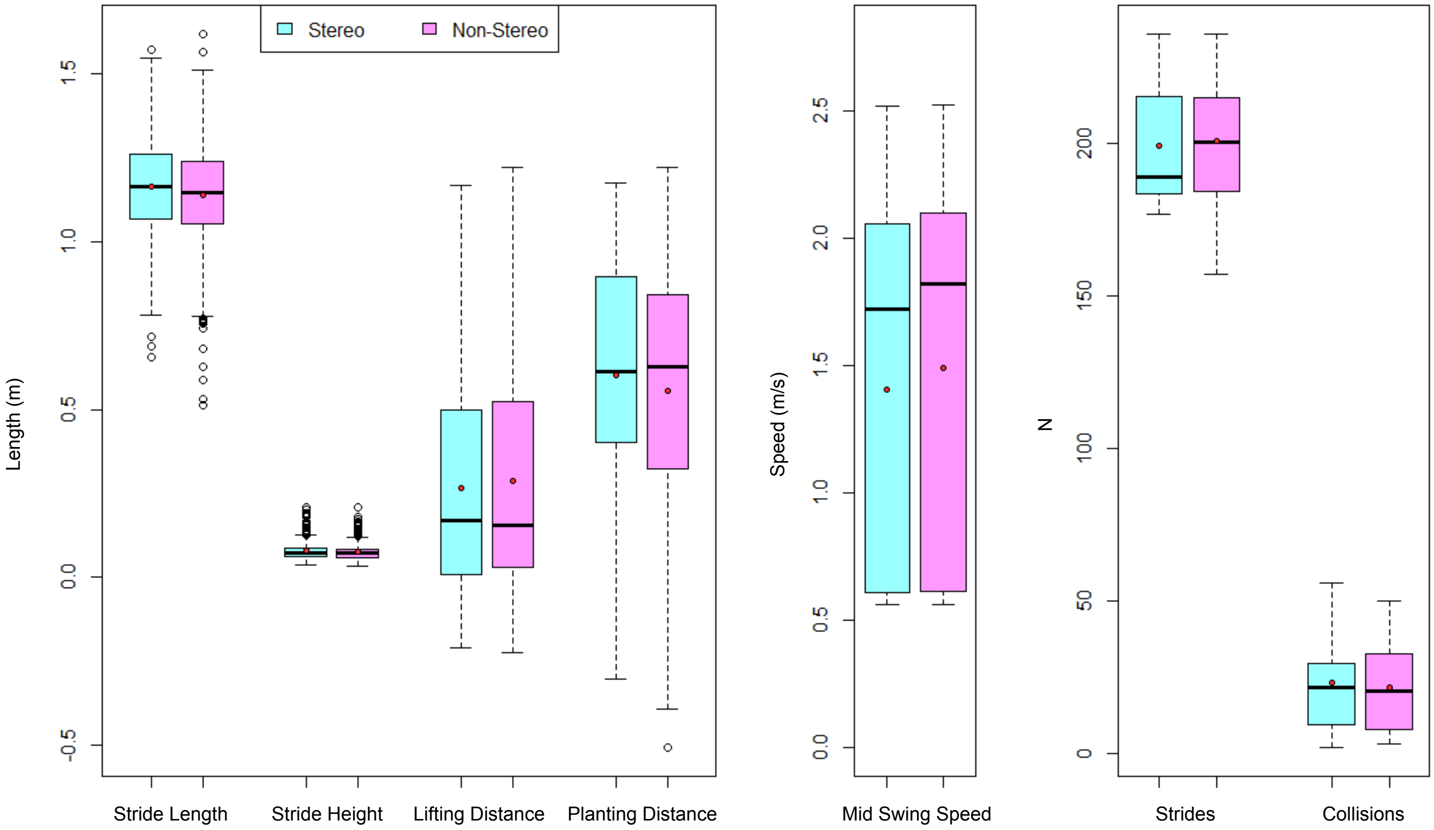

Fig. 12: Gait Parameters on stepping over gaps by viewing condition (red dots denote mean values; the boxes of the number of strides and the number of collisions denote the data distribution of that of all walking trials of each viewing condition across participants; for other gait parameters, the boxes denote the data distribution from the gait parameters of all gait cycles that covered an gap for each viewing condition. Box plot convention is as in Figure 8).

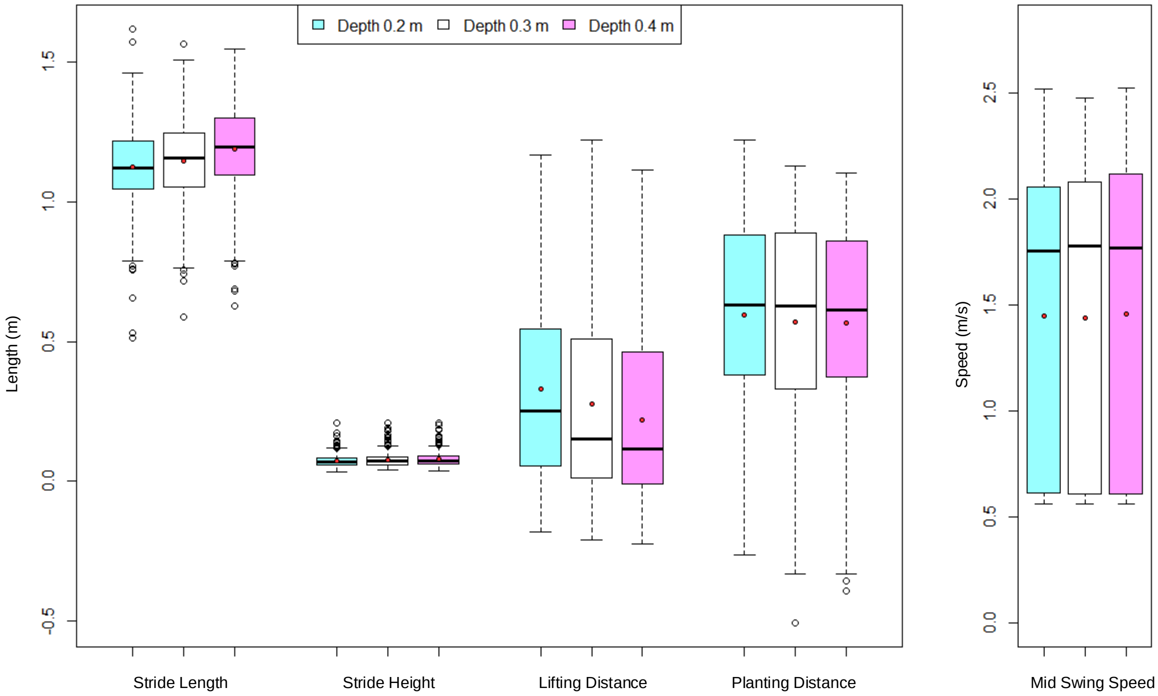

Fig. 13: Gait parameters on stepping over gaps by depth level (red dots denote mean values; the boxes of these gait parameters denote the data distribution from the gait parameters of all gait cycles that crossed a gap for each level of gap depth. Box plot convention is as in Figure 8).

TABLE 2: Results of the Linear Mixed-Effects Models analyses on stepping over gaps

		l_s	h_s	d_l	d_p	s_f
Viewing Condition	$F(1, 1185)$	13.01	4.87	1.94	8.68	5.35
	p	**<0.001**	**0.028**	0.164	**0.003**	**0.021**
	η_p^2	0.011	0.004	0.002	0.007	0.004
Depth Level	$F(2, 1185)$	29.12	6.31	17.36	1.27	0.09
	p	**<0.001**	**0.002**	**<0.001**	0.281	0.913
	η_p^2	0.047	0.011	0.028	0.002	0.000
Viewing Condition × Depth Level	$F(2, 1185)$	0.24	0.68	0.91	1.22	1.87
	p	0.789	0.508	0.404	0.297	0.154
	η_p^2	0.000	0.001	0.002	0.002	0.003

		n_s	n_c
Viewing Condition	$F(1, 29)$	0.25	0.35
	p	0.618	0.561
	η_p^2	0.009	0.012

Note: Significant p-values ($p \leqslant 0.05$) are in bold.

firmed by shorter stride length, decreased foot lifting distance to obstacles and increased foot planting distance to obstacles under the stereoscopic viewing condition compared to the non-stereoscopic viewing condition. Mid swing speed was lower under stereoscopic viewing than that of non-stereoscopic viewing. People tended to lift their feet higher when they encountered obstacles with a height of 0.3 m under the stereoscopic viewing condition, implying less tripping hazards. Cadence under stereoscopic viewing was higher than non-stereoscopic viewing. But avoiding collision with obstacles was equally difficult between viewing conditions. In addition, people adjusted their footsteps when they encountered obstacles with different heights during walking. This was reflected in the differences of stride length, stride height, foot lifting distance and foot clearance to obstacles between levels of obstacle height.

5 EXPERIMENT 2: STEPPING OVER GAPS

5.1 Introduction

While obstacles protruding from the ground presented in Experiment 1 are clear to human vision, we are also interested in gaps that are less obvious to vision when viewed at a distance. Furthermore, traversing a gap requires control of the length of the step while raised obstacles also require control of the toe clearance. The goal of the experiment was to investigate whether stereoscopic viewing provides advantages when people step over gaps.

5.2 Design

In this experiment, we designed an indoor virtual environment that consisted of a ground surface with gaps, two side walls and a celling shown in Figure 4. A console view of the scene on the host machine is shown in Figure 5. These geometries were textured using different stone images to create contrasts between the ground, walls and the ceiling. Here, we referred to the negative height of the ground surface to the bottom of the gaps as deepness (y-axis) and the distance between the front edge of a gap to the back edge of a gap as depth (z-axis). The width (x-axis) and the deepness (y-axis) of the gaps were fixed as 10 m and 0.5 m, respectively. The depth (z-axis) of the gaps had three different values, which were 0.2 m, 0.3 m and 0.4 m. As in the previous experiment, each condition (i.e. depth) was repeated ten times. Thus, in an experimental scene, there were thirty gaps in total and the order of the gaps were randomized. The distance between the participant and the front edge of the first gap was 5 m and the distance between the back edge of a gap and the front edge of its immediate successor was 3 m. The total length of each walking path was approximately 100 m. Participants were also expected to perform constant speed linear walking in the virtual environment.

As in the previous experiment, each generated experimental scene was considered as a single trial and participants were asked to perform two training trials under the stereoscopic viewing condition, subsequently followed by two experimental trials under the stereoscopic viewing condition and two experimental trials under the non-stereoscopic viewing condition, with the order of experimental trials counter-balanced as in the previous experiment.

5.3 Participants

Ten people (5 males, 5 females, age: 20 - 39, height: 1.58 - 1.79 m) participated in the experiment. All had normal or corrected-to-normal vision. Stereo acuity of participants was verified using the Randot Stereotest (Stereo Optical Company, Inc. Chicago IL). All had good stereo acuity ($\leqslant$ 50 seconds of arc). Informed consent was obtained from all participants in accordance with a protocol approved by the Human Participants Review Subcommittee at York University.

5.4 Procedure

The procedure of experiment 2 was the same as that of previous experiment but virtual scenes with gaps instead of obstacles were presented.

5.5 Results and Discussion

Figure 7 shows a segment of recorded foot trajectories stepping over gaps. As in the previous experiment, we applied the method described in Section 3.2 on recorded foot positions to extract gait parameters. We then performed the Linear Mixed-Effects Models analyses (package NLME in R) using R 3.4.2. The independent factors involved were viewing conditions (stereoscopic and non-stereoscopic) and depth levels (0.2 m, 0.3 m and 0.4 m) of the gaps and the dependent factors were the gait parameters. Effect sizes were reported using partial eta squared η_p^2 (estimated from repeated-measures ANOVA analyses of the same form as the Linear Mixed-Effects Models analyses). Gap depth and viewing conditions were treated as fixed effects and participants were treated as a random effect. We also included an interaction term between viewing conditions and gap depth to investigate whether the effect of viewing conditions on gait depends on gap depth. Post-hoc pairwise comparisons were performed using Tukey's range tests. Figure 12 and Figure 13 show box plots on gait parameters and Table 2 summarizes the results of the Linear Mixed-Effects Models analyses. As in the previous experiment, we had 1200 data samples in total.

Viewing conditions significantly affected stride length l_s ($p < 0.001$), stride height h_s ($p = 0.028$), foot planting distance to gaps d_p ($p = 0.003$) and mid swing speed s_f ($p = 0.021$) but did not affect foot lifting distance to gaps d_l ($p = 0.164$). As can be seen in Figure 12, the stereoscopic viewing condition tended to result in larger stride height and stride length. Logically, this was advantageous as larger stride length and stride height would help people avoid stepping into gaps. Although the analysis on foot planting distance did not reach statistical significance, the mean value of the parameter under stereoscopic viewing condition was generally smaller than the non-stereoscopic viewing condition, which meant that participants tried to step as close to the front edges of gaps as possible before walking over them. The result was consistent with Experiment 1. We also found that foot planting distance to the back edges of gaps was also larger under stereoscopic viewing condition than the non-stereoscopic viewing condition. The result was meaningful in the sense that if we wish to safely step over a gap, a reasonable strategy is to first step as close to the front edge of the gap as possible with a foot, then make a stride to go over the gap with the other foot and plant the foot as far as possible to the other edge of the gap to avoid being tripped or trapped. The result verified that stereoscopic vision supported this strategy. We speculated that if the distance between the front edge and back edge of gaps were designed larger with a treadmill that has a longer belt, the effect on lifting distance to gaps might be significant as participants would have to step very near the front edge of the gaps and accurately make strides long enough to cover gaps. The mean value of mid swing speed s_f was lower under the stereoscopic viewing condition than the non-stereoscopic viewing condition.

Similarly, for depth levels, there were significant effects on stride length l_s ($p < 0.001$), stride height h_s ($p = 0.002$), foot lifting distance to gaps d_l ($p < 0.001$) but not on foot planting distance to gaps d_p ($p = 0.281$) and mid swing speed s_f ($p = 0.913$). Tukey's range tests revealed that there were significant differences between depth level 0.2 m and 0.4 m and between depth level 0.3 m and 0.4 m on stride length l_s; and significant differences between depth level 0.2 m and 0.3 m and between depth level 0.2 m and 0.4 m on stride height h_s and foot lifting distance to gaps d_l. Thus, people adjusted their footsteps for gaps with different depths.

There were no interaction effects between viewing conditions and depth levels on gait parameters and there were no significant effects on number of strides n_s ($p = 0.618$) and number of collisions n_c ($p = 0.561$) between viewing conditions. The result on number of collisions suggested that it was equally difficult to avoid collisions with gaps under stereoscopic viewing and non-stereoscopic viewing in virtual environments.

5.6 Summary of the Results

Experiment 2 found that the stereoscopic viewing condition helped people step over gaps more safely as the stereoscopic viewing condition tended to result in larger stride height and stride length, which increased the chance to successfully step over gaps compared to the non-stereoscopic viewing condition. The stereoscopic viewing condition also enabled more accurate movements as the foot lifting distance to gaps was smaller and the foot planting distance to gaps was larger under the stereoscopic viewing condition. Mid swing speed was lower under stereoscopic viewing condition than that of non-stereoscopic viewing condition. No difference was found on the number of strides and number of collisions between viewing conditions. In addition, people adjusted their footsteps when they encountered gaps with different depths. This was shown in terms of stride length, stride height and foot lifting distance to gaps.

6 GENERAL DISCUSSION

Comparing the results of gait performance on stepping over obstacles and stepping over gaps, we found that stereoscopic viewing increased the number of strides significantly when stepping over obstacles but did not have a significant effect on cadence while stepping over gaps. We suspected that stepping over obstacles was a more stressful and challenging task than stepping over gaps, hence making smaller strides increased the flexibility in adjusting footsteps before stepping over obstacles. Stereoscopic viewing helped people to make smaller strides to perform more accurate movements. We also found that for both cases, mid swing speed was significantly slower under stereoscopic viewing than non-stereoscopic viewing. This probably meant that stereoscopic viewing allowed better control of lower limbs, which resulted in lower mid swing speed. In addition, stereoscopic viewing shortened the foot lifting distance to the front of obstacles and gaps and increased the foot planting distance to the back of obstacles and gaps. This generally increased the chance to successfully step over obstacles or gaps, as given limits on the maximum stride length that a person can make, shortening the lifting distance to obstacles or gaps makes it more likely to plant the foot successfully after obstacles or gaps. Finally, we found that avoiding collision with obstacles or gaps was equally difficult in virtual environments under stereoscopic viewing and non-stereoscopic viewing conditions. Although people were able to make a stride with enough length and height, the trajectories of their feet may still collide with the bounding boxes of obstacles or gaps. A probable reason was that force feedback or other types of feedback, including visual or sound, were lacking in the VR system. People were not aware when their feet collided with the bounding boxes so it was not possible or necessary for people to make improvement on their stepping. We opted not to include feedback into our experiments as we intended to isolate how stereoscopic and non-stereoscopic viewing conditions affect gait. We also noted that the effect sizes of the parameters we studied were generally small.

In addition to treadmills, other walking platforms such as the Virtuix Omni or the Cyberith Virtualizer could be integrated with the WISE. These allow people to turn and to walk with self-selected speed in VR. More complex experimental scenarios can be designed based on these platforms. On the other hand, several different WIP approaches [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] have been developed and they are important for practical VR approaches, it may be worthwhile to investigate how stereoscopic viewing affects walking performance with these techniques. As mentioned in the beginning of the paper, Redirected Walking [12] [13] introduces a turning factor during locomotion, this also can be studied in future research.

Matthis and Fajen [34] found that walkers relied on visibility of the ground at least two steps ahead to locomote normally. If the visibility is less than two steps, walkers will have problems in avoiding obstacles. Their experimental approach was to project color blobs onto floor with different levels of visibility range in real-time while participants were walking. For future research, we could conduct a similar study to examine the effects of occluded visual field on gait in virtual locomotion by masking the projected image on the display using the VR paradigm presented in this paper.

7 CONCLUSION

In this paper, we presented two VR walking experiments to investigate the role of stereoscopic viewing during continuous walking. Our results showed that stereoscopic viewing helped people to step over obstacles and gaps more accurately under constant motion during continuous walking in virtual environments. A primary implication of the results is that it reinforces the importance of rendering stereoscopic images to users during continuous locomotion tasks in VR. Rendering stereoscopic images to both eyes requires additional rendering passes from two different eye positions, and our research showed it is beneficial to render stereoscopic images despite the additional computational expenses as stereoscopic images enable users to perform more accurate walking movements in virtual environments. As walking in VR is different compared to walking in the real-world in terms of walking dynamics [24] and the perception of walking speed [25], further investigation is required to examine whether the results obtained in our study apply to real-world scenarios. In addition, we also found that stereoscopic viewing helped people to lift their feet higher for obstacles with a height of 0.3 m but had no effect for smaller obstacles. Further research should investigate the threshold of the height of obstacles where stereoscopic vision influences stride height.

To conclude, the current study suggests that providing binocular cues to VR displays is essential to design VR systems as binocular cues make stepping movements more accurate. One type of VR locomotion game, where this would be important, requires users to walk or run in virtual environments while avoiding obstacles using a locomotion interface for physical exercise or for fun. One can expect that by using a VR display with binocular cues, such gaming experience will resemble the experience in the real-world. This will make VR locomotion games more interesting and appealing to people.

ACKNOWLEDGMENTS

This research was supported by a National Science and Engineering Research Council of Canada Discovery Grant RGPIN-06732-2015 to R. Allison and infrastructure funding from the Canadian Foundation for Innovation (project #30859).

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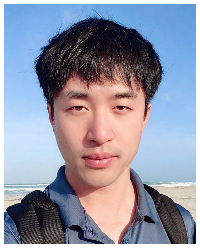

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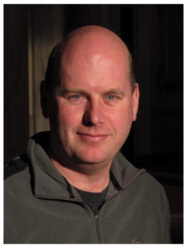

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