

Evaluating and Comparing Game-controller based Virtual Locomotion Techniques

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Abstract

The incremental hardware costs of virtual locomotion are minimized when the technique uses interaction capabilities available in controllers and devices that are already part of the VE system, e.g., gamepads, keyboards, and multi-function controllers. We used a different locomotion technique for each of these three devices: gamepad thumb-stick (joystick walking), a customized hybrid keyboard for gaming (speedpad walking), and an innovative technique that uses the orientation and triggers of the HTC Vive controllers (TriggerWalking). We explored the efficacy of locomotion techniques using these three devices in a hide and seek task in an indoor environment. We measured task performance, simulator sickness, system usability, perceived workload, and preference. We found that users had a strong preference for TriggerWalking, which also had the least increase in simulator sickness, the highest performance score, and highest perceived usability. However, participants using TriggerWalking also had the most object and wall-collisions. Overall we found that TriggerWalking is an effective locomotion technique and that it has significant and important benefits. Future research will explore if TriggerWalking can be used with equal benefits in other virtual-environments, on different tasks, and types of movement.

CCS Concepts

•Human-centered computing → Virtual reality; Usability testing; Graphics input devices;

1. Introduction

Relatively low cost, simplicity of operation, and availability of content development tools for consumer grade Virtual Reality (VR) systems are leading to their increased adoption and use. A critical element of such systems is how easy it is for users to move from place to place in the Virtual Environment (VE). This movement, enabled by a virtual locomotion technique, is arguably the most important affordance of any VE system. Virtual locomotion techniques almost always require that user interface devices and/or sensors (e.g., trackers) be part of the system. Using data received from the devices, locomotion techniques set both *speed* and *direction* of movement. For mass market VE applications such as 3D games, implementing virtual locomotion using the affordances of user interface devices that are already part of the system, e.g., game controllers, not only saves money, but builds on users' familiarity with the devices.

The study reported here evaluates and compares three virtual locomotion techniques that employ interaction peripherals commonly used with or included in gaming and/or VE systems: joysticks, keyboards, and spatial controllers. Study participants

(N=15) performed a "find and collect" task in a model of a furnished house, exercising their ability to use the different locomotion techniques to move through a crowded space. Using a counter-balanced, within subjects, repeated measures design, we compared the three locomotion techniques on: efficacy (score (the number of items collected), number of collisions, time), simulator sickness, general usability, task load, and preferences. The novel aspects of this work are:

- We implemented a locomotion technique for a *hip-worn* SpeedPad. While the keyboard interface for locomotion is familiar to many, locating the SpeedPad on the hip will be new to users, possibly negatively effecting their performance.
- Using a variety of behavioral (objective) and questionnaire (subjective) measures, we compared the usability of Xbox thumb-stick locomotion, SpeedPad locomotion, and the recently introduced TriggerWalking locomotion technique.

This exploratory study showed us that users prefer TriggerWalking to the other two techniques; simulator sickness measures were lowest for TriggerWalking but dizziness and nausea were reported by 1/3 of participants; measured usability varied little, but seven (7) users reported difficulty using one or the other of the devices; task load was a little lower for the SpeedPad, and users could find and collect objects successfully in all conditions, but had significantly

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more collisions using TriggerWalking. Based on our data, there is further work to be done to identify causes and ways to mitigate nausea and high collision counts.

2. Background

Virtual locomotion for VE users has been a topic of research and development since the very early days of virtual reality. Early techniques included using real treadmills [AB89] and virtual treadmills, the latter is a technique we now call Walking-in-Place (WIP) [SUS95b]. An early experiment comparing locomotion methods (WIP and joystick flying) was reported by Slater et al. [SUS95a]. That study was replicated with the additional condition of real walking [UAW*99] and the results were confirmed: Both studies showed that locomotion interfaces that were more like real walking elicited higher levels of presence than other conditions. A study conducted by Zambaka et al. [ZLB*05] compared the differences in cognition and understanding in a virtual environment of a small room comparing joystick-based travel techniques with real walking. The results suggest that the participants scored higher in the real walking conditions compared to joystick-based travel techniques. Wilson et al. [WKMW16] compared walking, WIP and an arm swinging technique [MXM*15], and confirmed that participants had more spatial awareness in real walking and WIP compared to the arm swinging technique. To aid understanding of the large number of methods of locomotion, Bowman, Koller, and Hodges [BKH97] proposed a taxonomy of locomotion techniques that, though published in 1997, is still very useful. The taxonomy has three parts: method of setting motion speed, method of setting motion direction, and type of input signal (continuous, stop/start, system controlled). The book *Human Walking in Virtual Environments: Perception, Technology and Applications* is a recent (2013) comprehensive reference on virtual locomotion theory and methods [SVCL13].

We chose our dependent variables to assess many of the characteristics of a good locomotion technique as they are presented in the literature [BKH97, WP13]. Table 1 shows the quality factors we studied and the measures we used to assess them. Each of the questionnaires we employed, the 1993 Simulator Sickness Questionnaire (SSQ) [KLBL93], the 1988 Standard Usability Scale (SUS) [Bro96], and the 1988 NASA Task Load Index (NASA-TLX) [HS88], is the generally accepted *de facto* standard instrument for measuring its respective phenomena. Each has a long history of use in the human factors community and more recently in VE evaluation studies.

3. System

This paper compares the usability of three game-controlled based locomotion techniques:

- GamePad locomotion using a thumb-stick
- SpeedPad locomotion using key strokes
- TriggerWalking using controller triggers

In this section, we describe how each technique works.



Xbox Wireless Controller

Nostromo SpeedPad n52

Figure 1: Xbox controller and SpeedPad

3.1. GamePad Thumb-stick Locomotion

Participants control their speed of movement using the left thumbstick of a Microsoft wireless Xbox controller as shown in Figure 1. Speed, rate of change in the user's viewpoint, is scaled linearly with the displacement of the thumbstick from its center rest position. Maximum speed, capped at 0.9 m/s, is achieved when the thumbstick is pushed to its maximum in one direction. Direction of motion is set to be the user's view direction as measured by the Lighthouse tracker and the HTC Vive HMD.

3.2. Hip-mounted SpeedPad Locomotion

The Belkin Nostromo SpeedPad n52 is a keyboard game controller peripheral as shown in Figure 1. In our system, it was mounted on the user's left hip and operated with the left hand. The SpeedPad's keypad was used for locomotion in the VE, using typical first-person controls: '03' was used for going forward, '08' for backward, '07' for strafing left and '09' for strafing right. These keys are physically arranged in the same pattern as WASD on a standard keyboard. A tape with rough surface was pasted on the keys used for the locomotion to make sure that the users identified the keys to use while they were wearing an HMD.

The user's view direction as derived from the Vive HMD pose which establishes "forward" for the frame of reference of the SpeedPad. For each keypress, the user's viewpoint is moved 0.9 m/s in the direction appropriate to the key.

3.3. TriggerWalking Locomotion

TriggerWalking is a locomotion technique inspired by the biomechanics of human walking [SHSL17]. It enables realistic walking by replacing the legs with the triggers of the common spatial

Locomotion Interface Quality Factor	Measure
Speed Control	Time
Positional Accuracy	Score and Collisions
Information Gathering (while moving)	Score (finding and collecting objects)
Easy to Learn	SUS Usability, Preferences
Easy to Use	SUS Usability, Preferences
No Increase in Sim. Sickness	SSQ
Low Cognitive Load	NASA-TLX

Table 1: Quality factors and Measures

controllers; the aim is to accomplish near-realistic walking without physically moving the legs. The velocity of walking can be controlled by increased step length or increased gait speed. An increase in trigger frequency increases the frequency of the "steps," and the step length can be manipulated using the angle between the controller and the ground plane. In the neutral (rest) position of the controllers, the velocity is equivalent to 0.7 m/s and as the angle increases to 90°, the speed approaches the maximum 0.9 m/s. The direction of walking is the average of the yaw direction of both the controllers. As a demonstration, TriggerWalking can be imple-

Locomotion Technique	Speed Control	Direction Control
GamePad	How far stick is pushed	User view direction
SpeedPad	Constant speed based on key press	User view direction
Trigger Walking	<ul style="list-style-type: none"> Step frequency by increasing the frequency of triggering the Vive controller. Step length by angle of controllers relative to the floor. 	Average of the yaw angles of the two controllers

Table 2: Speed and direction settings for the locomotion techniques

mented for the Touch controllers of the Oculus Rift for seated or standing use. It can also be implemented with HTC Vive controllers as used in this user study. To provide a realistic VR walking sensation for TriggerWalking, head oscillations are simulated. The types of camera oscillations include vertical and lateral.

4. Methodology

To analyze the usability, simulator sickness and physical demand of the three locomotion techniques, we conducted a within subject, repeated measures user study with locomotion technique as an independent variable with three levels: GamePad (GP), SpeedPad (SP), and TriggerWalking (TW).

4.1. Participants

This experiment is approved by our University Human Ethics Committee. All participants read and signed the consent form. There were 15 participants, eight male and seven female with an average age of 30. All participants had normal (5) or corrected to normal eyesight (10). All participants but one were right-handed. Eight participants had good knowledge of 3D games; eight participants play 3D Computer games on a weekly basis.

4.2. Equipment

The study was conducted in a 7m x 5m room and we used an HTC Vive HMD, which provides a resolution of 1080 x 1200 pixels per eye. The diagonal field of view is 110° with refresh rate of 90 HZ. The pose (position and orientation) of the HMD in all

conditions and the pose of the Vive controllers in the TW condition were tracked using the Lighthouse tracking system. For the GP condition, we used the left thumb-stick on the Microsoft wireless Xbox controller. We used the Belkin Nostromo SpeedPad n52 for the SP condition. The specifications of the computer used in the study were an Intel Core i7-6700 processor, 16GB of main memory, and an NVIDIA GeForce GTX 1080 graphics card.

4.3. Virtual Environment

The VE was rendered using the Unity3D game engine version 5.5, and was a realistic model and rendering of the interior of a house that had six rooms and a corridor connecting the rooms as shown in Figure 2. Navigation in the house was somewhat difficult, due to the presence of tables, chairs, beds, cabinets, indoor plants, and other furnishings.



Figure 2: Participant view of the virtual environment

To prevent users from hitting or trying to walk through walls or objects, we implemented collision detection. When a collision with a wall or object is detected, the display fades to black indicating to the participant that they are in collision and should move away.

4.4. Task

We placed 12 Easter eggs in the house and asked participants to find and pick up all the eggs within three minutes. Each participant



Figure 3: Screen-shots of the Easter eggs according to their difficulty

performed the task three times with a different egg arrangement each time. Each egg arrangement had six easy-, four medium-, and two hard-to-find eggs as illustrated in Figure 3.

- **Easy:** Easter eggs are fully visible.
- **Medium:** Easter eggs are partially visible in corners or between tables, but some effort is needed to find them.
- **Hard:** Easter eggs are placed below chairs or behind objects, and participants must search the area thoroughly to find the eggs.

In the GP condition, participants move using the left thumbstick. Eggs were collected by moving towards the egg and pressing the 'A' button on the Xbox controller. In the SP condition, participants use 'WASD' to move around the environment. Eggs were collected by moving towards the egg and pressing the left alt button. In the TW condition, participants navigated in the environment using the triggers of the Vive controllers. To pick-up the eggs, they had to touch the egg with the right controller.

4.5. Experimental Session and Measures

Participants were introduced to the equipment used in the experiment and were informed in detail about the tasks and conditions. They then had a short training session on each technique. When the participants indicated they were ready, the experiment environment was loaded and the participant was instructed to find and pick up the eggs within three minutes. This was repeated for the other two locomotion conditions. Since each participant completed the task three times, to mitigate any effect of order of conditions, the order of conditions was counterbalanced across participants.

We collected demographic information with a questionnaire before the experiment. In addition to gender and age, this included information about knowledge of and frequency of playing 3D games. Participants completed the Simulator Sickness Questionnaire (SSQ) to provide a baseline value for use in later analyses. Time to complete the task was measured. However, since the time was capped at three minutes, most of the participants used the entire allotted time. The number of eggs collected, the *Score*, was measured to compare the efficiency of the techniques, i.e., how well users could find and collect the eggs.

We administered three standard questionnaires after each trial run to evaluate and compare our techniques on the interface quality factors as shown in Table 1. The questionnaires are:

- *Simulator Sickness* was measured using the Kennedy-Lane SSQ before the experiment and after each task condition.
- *Usability* of the techniques was measured using the Standard Usability Scale (SUS) questionnaire. This is a ten-item questionnaire with responses on a 5 point Likert scale. (Note that, confusingly, this is not the Slater, Usoh, Steed Presence questionnaire!)
- *Task Load Index* was measured using the NASA Task Load Index (NASA-TLX). The NASA-TLX measures Mental demand, Physical demand, Temporal demand, Performance, Effort, and frustration.

In addition to these questionnaires, after their three trials were completed, participants were asked to rate their preference for each of the three locomotion techniques on an 11-point scale and explain their high and low scores.

5. Results

The statistical analyses were performed using SPSS 24 for Windows. For ordinal data, related-sample non-parametric tests were used. For other data, a repeated measures GLM was used. Pairwise comparisons were corrected using SIDAK when appropriate. Significance level was set to 0.05 and to 0.1 for marginal significance.

5.1. Performance Metrics

To measure the difference in performance for different techniques, we measured Score, Time, and Collisions. As shown in Table 3, the mean score for TW has highest score followed by SP and GP, respectively. Since there was a restriction on time, the mean time taken (in seconds) to pick up the eggs was nearly three minutes, with GP (Mean=173.27) having slightly lower time taken than TW (M=175.53). The number of collisions was significantly higher in the TW condition (M=68.8) than SP (M=46.6) and GP (M=0.6).

Measure	GP	SP	TW
Score	$\bar{x} = 9.2$ $s = 0.38$	$\bar{x} = 9.4$ $s = 0.56$	$\bar{x} = 10.27$ $s = 0.40$
Time	$\bar{x} = 180.0$ $s = 0.00$	$\bar{x} = 173.3$ $s = 3.94$	$\bar{x} = 175.5$ $s = 2.60$
Collisions	$\bar{x} = 50.6$ $s = 3.90$	$\bar{x} = 46.6$ $s = 4.92$	$\bar{x} = 68.8$ $s = 7.44$

Table 3: Mean and SE of Score, Time, and Number of collisions

The differences between scores were marginally significant ($p=0.089$). The score of TW (M=10) was marginally significantly higher than GP (M=9, $p=0.064$) and SP (M=9, $p=0.084$). The difference between GP and SP was not significant ($p=0.683$) Figure 4 shows the graph of mean scores of participants in all the three conditions.

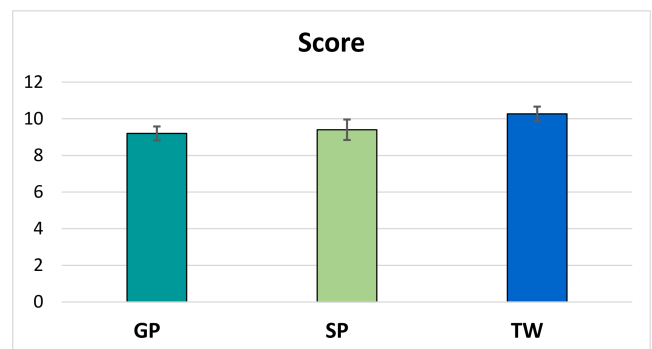


Figure 4: Score

The difference between number of collisions was significant ($p=0.018$) as shown in Figure 5. Participants using TW had the most collisions (M=69) compared to GP (M=47, $p=0.011$) and SP (M=51, $p=0.047$). The difference between GP and SP was not significant ($p=0.337$).

The differences in Time between the three conditions was not

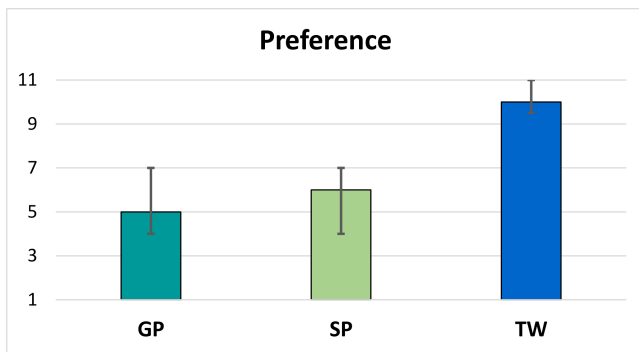


Figure 5: Collisions (Mean, SE)

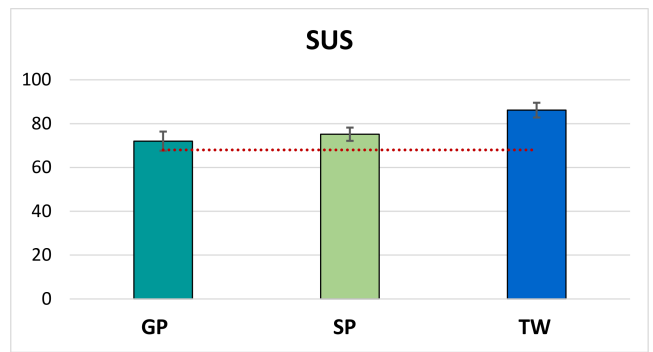


Figure 7: System Usability Scale (Mean, SE, Usability threshold)

significant ($p=0.157$), with GP ($M=173.3$), SP ($M=180$), and TW ($M=175.5$).

5.2. Questionnaires

Simulator Sickness Questionnaire

The data from the SSQ questionnaire suggest that the increase of simulator sickness from baseline was the lowest in TW ($M=17.56$) compared with the other two conditions: GP ($M=142.65$) and SP ($M=142.76$) as seen in Figure 6.

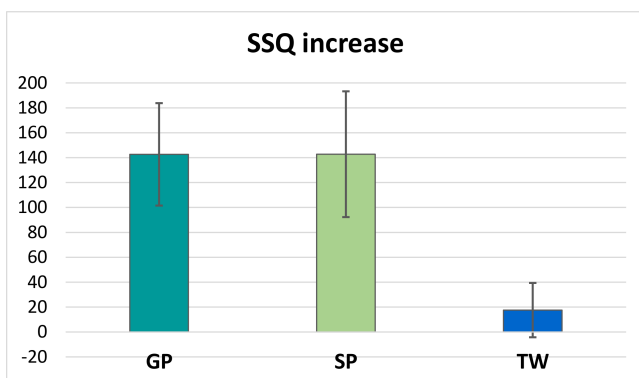


Figure 6: Simulator Sickness Questionnaire (Mean, SE)

The difference between SSQ rating was statistically significant ($p=0.005$). The SSQ score of TW was significantly lower than GP ($p=0.009$) and marginally significantly lower than SP. There was no significant difference between SSQ changes for GP and SP.

5.3. System Usability Scale

The difference between SUS scores was significant ($p=0.017$). Participants rated TW ($M=86$) to have the highest usability compared with GP ($M=72$, $p=0.041$) and SP ($M=75$, $p=0.064$) as shown in Figure 7. The difference between GP and SP was not significant ($p=1.00$).

NASA Task Load Index

The differences between GP ($M=47$), TW ($M=43$) and SP ($M=48$) were not significant ($p=0.24$). Figure 8 shows the mean scores of NASA TLX questionnaire.

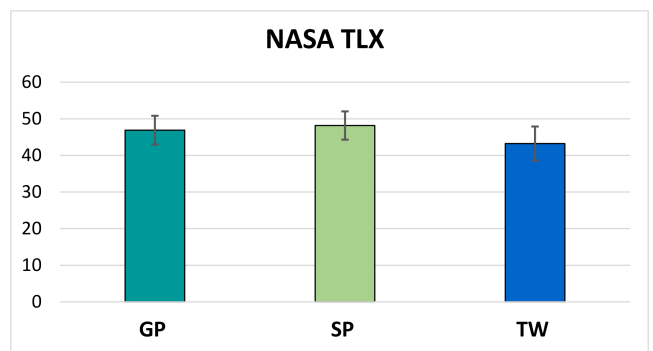


Figure 8: NASA TLX (Mean, SE)

5.4. Preference

Participants had a strong and significant difference in preference ($p<0.001$). TW was the preferred choice (Median=10) ($p=0.003$) compared to GP ($p=0.004$) and SP ($p=0.003$), respectively. The difference between GP (Median=5) and SP (Median=6) was not significant ($p=0.548$) as shown in Figure 9.

Table 4 shows the mean and standard error values of SSQ scores (incr.), SUS scores and NASA TLX.

Measure	GP	SP	TW
SSQ (incr.)	$\bar{x} = 142.65$ $s = 41.13$	$\bar{x} = 142.76$ $s = 50.5$	$\bar{x} = 17.56$ $s = 21.8$
SUS	$\bar{x} = 72$ $s = 4.387$	$\bar{x} = 75.17$ $s = 3.37$	$\bar{x} = 86.17$ $s = 3.03$
NASA TLX	$\bar{x} = 46.89$ $s = 3.93$	$\bar{x} = 48.16$ $s = 3.86$	$\bar{x} = 43.23$ $s = 4.66$

Table 4: Mean and SE of SSQ, SUS and NASA TLX

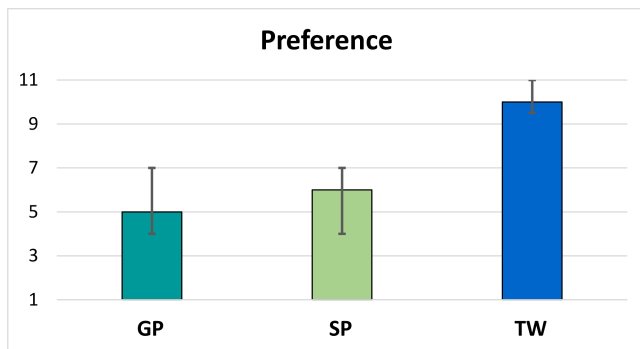


Figure 9: Participants' preference rating (Median, IQR)

A thematic analysis was performed on the comments provided by the participants at the end of the study. The analysis showed that a main problem associated with GP use was that it increased symptoms of simulator sickness (4 mentions) and disorientation (2 mentions). One participant also named simulator sickness as the main negative experience with the use of SP. Lower performance associated with the use of GP was mentioned twice. Concerns with the ease of use and unfamiliarity within the interface were additional criticisms of SP, and was mentioned five times. The use of TW was criticized once as too inconvenient because it required more body movement than the other two interfaces. However, TW was rated positively by participants because of the lower impact on simulator sickness (3 mentions), its support for better performance (4 mentions) and the highest ease of use and naturalness of the user interfaces (11 mentions).

6. Discussion

Overall, the mean Score in all conditions was similar, with TW having a slightly higher score than the other two conditions. Since each environment had six easy and four medium eggs, most of the participants had a Score value of 10, however picking up the last two (hard) eggs needed careful observation. This may be one of the reasons for the mean value of Score being around 10. There was a Time cap of three minutes for completing the task in order to make the task more challenging and engaging. The mean Time taken over all the conditions was three minutes, showing a ceiling effect. The number of Collisions in the virtual environment while using TW was significantly higher when compared to the GP and SP conditions. The ability to move much faster by increasing the trigger frequency could be one of the reasons for the higher number of collisions. There is little ability to change speed with the GP and SP techniques.

While we did not measure other quality factors directly, the open-ended participant comments addressed some of them, e.g., comments on disorientation apply to the quality factor "spatial awareness and orientation." Three factors are related to equipment and can be directly observed. Locomotion techniques should require: minimal additional infrastructure (none in our case), minimal encumbrances worn or carried by the user (no additional devices in our case), and hands-free operation (only half true for our

techniques). The ability to elicit the illusion of presence is a very important quality factor for VE systems. As our focus was on locomotion, we did not measure presence.

Participants using artificial locomotion techniques such as GP and SP experienced significantly high simulator sickness compared to TW, and these results support previous findings. Simulator sickness and disorientation were also the main reasons for GP and SP having low preference levels. The SUS scores of the different conditions suggest that TW is more usable for locomotion compared to GP and SP. The ability to control the movement using the controllers was perceived as easy and realistic, however one participant criticized it as being inconvenient.

7. Summary and Future Work

In this study, we compared and evaluated the usability of three controller-based locomotion techniques to navigate in virtual environments. We implemented and compared locomotion techniques for an Xbox GamePad, a Belkin Nostromo SpeedPad gaming keyboard, and TriggerWalking. From the results, we found that the performance with the GamePad and SpeedPad were similar and that both were fairly accurate. Overall, however, TriggerWalking showed better efficacy and was the participants' preference. Furthermore, TriggerWalking induced less simulator sickness compared to the GamePad and SpeedPad.

While this study investigated the performance of various devices in a realistic indoor environment, it remains to be seen if similar results can also be obtained for outdoor environments or different tasks. Furthermore, the reasons behind the significant number of collisions in TriggerWalking will be explored. Though TriggerWalking is a controller-based locomotion technique, it embeds elements of the biomechanics of human gait. Hence, it will be compared to natural and semi-natural locomotion techniques, such as WIP, arm swinging, and redirected walking. Finally, we are also interested in studying the performance and cognitive load of TriggerWalking compared to other techniques in small, medium, and large virtual environments.

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