

Comparing the Performance of Natural, Semi-Natural, and Non-Natural Locomotion Techniques in Virtual Reality

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ABSTRACT

One of the goals of much virtual reality (VR) research is to increase realism. In particular, many techniques for locomotion in VR attempt to approximate real-world walking. However, it is not yet fully understood how the design of more realistic locomotion techniques affects user task performance. We performed an experiment to compare a semi-natural locomotion technique (based on the Virtusphere device) with a traditional, non-natural technique (based on a game controller) and a fully natural technique (real walking). We found that the Virtusphere technique was significantly slower and less accurate than both of the other techniques. Based on this result and others in the literature, we speculate that locomotion techniques with moderate interaction fidelity will often have performance inferior to both high-fidelity techniques and well-designed low-fidelity techniques. We argue that our experimental results are an effect of interaction fidelity, and perform a detailed analysis of the fidelity of the three locomotion techniques to support this argument.

Keywords: Interaction fidelity, Effectiveness, Locomotion interaction, Virtusphere.

Index Terms: I.3.6 [Methodology and Techniques]: Interaction Techniques; H.5.2 [User Interfaces]: Input Devices and Strategies.

1 INTRODUCTION

In virtual reality (VR), a significant amount of research has been focused on improving realism, or fidelity. It is often assumed that more realism is better and will lead to greater effectiveness (i.e., performance, usability or satisfaction). In particular, many VR technologies focus on improving the naturalness of locomotion by approximating human walking.

In most virtual environments (VEs), real walking throughout the entire space is not feasible, due to limited size of the tracked space. Devices such as omni-directional treadmills [4] and techniques such as walking-in-place [5] and redirected walking [22] are designed to simulate real-world walking to varying degrees, with the idea that users will be able to leverage their real-world experiences and skills to move through a VE effectively.

Locomotion with high realism may provide the user with better proprioceptive cues, enhance distance judgment, and increase the sense of presence [10], but it typically implies higher cost. Thus, understanding the comparative levels of effectiveness and subjective preference for locomotion interfaces with different levels of fidelity is an important research topic in VR.

As defined by Gerathewohl [7], *fidelity* is the degree to which a system accurately reproduces a real-world experience and its effects. Fidelity has several distinct aspects, including display fidelity and interaction fidelity [1]. *Display fidelity* is defined as the objective degree of exactness with which a system reproduces real-world sensory stimuli [18]. Researchers have reported

positive effects of increasing display fidelity on various parameters of effectiveness [2,23]. However, the effects of interaction fidelity are not as clear.

Interaction fidelity is defined as the objective degree of exactness with which a system reproduces real world interactions [18]. Increasing interaction fidelity has been shown, in some cases, to increase performance [9,17,19]. For example, manipulation techniques based on six-degree-of-freedom input devices outperformed techniques based on two-degree-of-freedom mice [9]. However, there are also studies with the opposite result, in which lower-fidelity techniques for travel or locomotion outperformed higher-fidelity techniques [16,17]. For example, “natural” interaction techniques for driving a vehicle in a racing game were significantly less effective than low-fidelity ones [16].

To gain a better understanding of these seemingly contradictory results, we tested three locomotion interfaces with different levels of fidelity. Our study compares high-fidelity real walking with a low-fidelity gamepad technique and the medium-fidelity Virtusphere locomotion interface [12]. The results contribute an improved understanding of the performance of locomotion techniques at varying levels of interaction fidelity. We discuss these results and their implications for VR interaction design.

2 RELATED WORK

A locomotion interface is a system or device that provides users with a sense of walking and enables them to translate and rotate in a VE. A high-fidelity locomotion interface creates an experience of physical walking in exploring a large VE while keeping the user in the boundaries of the physical environment [25]. To increase the match between proprioceptive cues and visual feedback, more natural interfaces and devices such as walking-in-place [5], omni-directional treadmills [4], the Virtusphere [12], and redirected walking [22], have been proposed.

The Virtusphere, one such device, is a large hollow sphere mounted on casters, in which a user wearing a head-mounted display (HMD) can walk in any direction, to move through a VE of any size. Skopp et al. [24] studied presence, overall involvement/control and sickness in the Virtusphere compared to a gamepad technique. Although the mean values of these metrics were better for the gamepad than for the Virtusphere, they did not observe any significant difference. Marsh et al. [13] performed a study on the effectiveness of training on performance and cognitive resource demands in the Virtusphere. They observed a positive effect of training on movement abilities and performance. Performance, simulator sickness and satisfaction have been studied for first-person and third person viewpoints in the Virtusphere [15]. The first-person viewpoint group performed better and enjoyed the system more, while the third-person group had less motion sickness and balance disturbance.

While there have been many studies comparing purely virtual travel techniques, relatively few studies have directly compared the performance of two or more higher-fidelity locomotion interfaces. Feasel et al. [22] compared five locomotion interfaces by measuring performance of locomotion tasks in terms of time and head trajectory length. Three of these interfaces used walking in real world, which outperformed the other two techniques including a low latency walking-in-place technique and a joystick

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technique. Additionally, Griffiths et al. [8] devised a set of VE tasks and tests to study the performance of navigation and object manipulation. However, it is not clear if higher fidelity leads to better performance. Before answering this question, we need to know how to evaluate the effect of fidelity for various interfaces.

2.1 Effects of Interaction Fidelity

To evaluate fidelity, some VR researchers have compared low-fidelity regular desktop systems to high-fidelity VR systems for different aspects of realism. Chance et al. [3] compared three locomotion interaction techniques, and found that the more natural techniques produced greater spatial orientation in users than the less natural ones. Techniques providing more integrated degrees of freedom (DOFs) for the task of 3D object manipulation [9] and rotation [19] were more effective. McMahan et al. [17,18] showed that pointing directly to a target is more effective than using a mouse to aim. Pausch et al. [19] showed that higher fidelity head tracking can increase user performance compared to hand-based view point control for a search task.

Other results show disadvantages of higher interaction fidelity. McMahan et al. [17] found that a semi-natural (human joystick) technique was outperformed by a non-natural (mouse and keyboard) techniques in a first-person 3D game. The racing game study mentioned in the introduction [16] is another example. These experiments compared higher and lower fidelity techniques, but it is unclear whether these results are generalizable.

McMahan et al. [17] posited that the overall level of interaction fidelity depends on a combination of system characteristics. They pointed out that each element of an interface may fall at a different location on interaction fidelity spectrum. This idea led to the Framework for Interaction Fidelity Analysis (FIFA) [18]. FIFA compares interaction techniques to their real-world counterparts across several dimensions.

2.2 Locomotion Interaction Effectiveness

Locomotion techniques with different levels of fidelity have been compared for performance. Peck et al. [20] compared a large-scale real-walking locomotion interface called Redirected Free Exploration with Distractors (RFED) to walking-in-place and joystick techniques for cognitive performance on navigation and wayfinding. The RFED technique was significantly better. Similar results were observed by Feasel et al. [5], for comparing high-fidelity techniques real walking and VRWalk to Low-Latency, Continuous-Motion Walking-in-Place (LLCM-WIP) and joystick techniques. Whitton et al. [26] compared three high-fidelity walking techniques, a low-fidelity flying technique using a joystick and a medium-fidelity technique of walking-in-place. For the performance metric of final distance to target, the walking-in-place technique was outperformed by the joystick technique, while for other measures such as peak velocity, walking-in-place was better than the joystick technique.

A study on cognitive implications of semi-natural locomotion interfaces was performed by Marsh et al. [14]. They compared a gamepad interface (least natural), the position-to-velocity (P2V) interface (slightly more natural) and real walking (completely natural baseline). They observed that gamepad and real walking significantly outperformed than the P2V interface, while they did not observe any significant difference between gamepad and real walking. In addition, the cognitive load of real walking was significantly less than both P2V and the gamepad interface.

3 EXPERIMENT

3.1 Goals and Hypotheses

To deepen our understanding of the performance of locomotion techniques at varying levels of fidelity, we designed an

experiment to directly compare a semi-natural locomotion technique with a non-natural technique and a fully natural technique. We used a gamepad technique based on a game controller for the non-natural interface, a real walking technique in a tracked area for the natural interface, and the Virtusphere device [12] as the semi-natural interface. The study tested the performance of the three interfaces on basic walking tasks for the measures of time and accuracy, as well as subjective measures.

Our hypothesis was that both the gamepad technique and the real walking technique would exhibit performance superior to the Virtusphere. We believe that non-natural techniques that are designed appropriately can yield good performance. Similarly, the real walking technique is highly natural and needs no adaptation by the user. On the other hand, the Virtusphere seems difficult to learn and use because of the differences between Virtusphere walking and real walking.

We designed a single-factor, within-subjects experiment to investigate this hypothesis. The independent variable was locomotion interface, with three levels (see section 3.3). The dependent variables were task completion time, path deviation, and participants' opinions of the interfaces (see section 3.5).

3.2 Apparatus

In all three conditions, the VE was displayed to the users with a Sensics zSight HMD with a FOV of 60°, resolution of 1280x1024, and stereoscopic rendering. The gamepad technique used a Sony DualShock 3 game controller with two thumbsticks used for locomotion. In the real walking technique, 16 OptiTrack Flex 3 cameras, with a resolution of 0.3MP each and a frame rate of 100fps, were used to track the HMD using a rigid body of reflective markers. The dimensions of the tracked space where the user could physically walk were about 12x12 feet. In the Virtusphere technique the HMD's orientation was tracked using the inertial sensors in a Sony Move controller attached to the display (Figure 1). We used the "Move.me" application on a Sony PlayStation 3 to perform orientation tracking using the Sony Move controller. The Virtusphere's rotation was tracked with its own optical tracker. We used WorldViz's Wizard 4.0 to interface with the hardware. The application software rendered the VE, managed the flow of the experiment, and logged user data.

3.3 Locomotion Interfaces

The gamepad technique was designed similar to a standard gaming interface in which translation (forward/backward and left/right) used a thumbstick controlled by the dominant hand while rotation (yaw and pitch) used the other thumbstick controlled by the non-dominant hand. The VE was displayed to



Figure 1 – The Virtusphere used in this study

the user with the HMD, and viewpoint was controlled by the joystick. The user was not head tracked for this technique (as would be typical in a desktop gaming setting), and viewing direction and moving direction were coupled. The maximum movement velocity with the gamepad was controlled to be equal to the average walking speed in real walking technique.

In the Virtusphere technique (Figure 1), the user's walking inside the Virtusphere was directly mapped (direction and scale) to viewpoint translation in the VE. The viewing direction and walking direction were decoupled. The Virtusphere's movement velocity was adjusted so that the average velocity was equal to the average walking speed in the real walking technique. For the real walking technique, users were physically walking in a tracked space, while wearing a tracked HMD. The user's position and orientation were mapped directly to the VE without scaling.

3.4 Tasks

A standardized training task involved walking along a straight line to reach the target. Participants were instructed to walk precisely on the line to reach the target. The training task was performed in a different 3D environment than the other tasks, and was intended to allow participants to become comfortable with all three locomotion interfaces.

In the experimental task, participants were asked to perform two walking tasks: straight and multi-segment lines. In the straight line task, participants walked on an indicated straight line to reach a target placed on the ground (Figure 2A) in a 3D art gallery environment. In the multi-segment task, the lines leading to the target included perpendicular turns (Figure 2B). Participants were asked to walk precisely on the line to twelve individual targets as quickly as they could. Audio and visual feedback told participants when each target had been reached. After reaching every target, the target and the indicating line disappeared, and the next target was revealed. All users were asked to perform two courses of each task (48 total targets), differing only in the order in which the target lines appeared, for each interface.

3.5 Measures

We used path deviation as a measure of accuracy. We defined path deviation as the perpendicular distance between the user's position in the VE and the indicated line. We recorded the perpendicular distance every 50ms, and calculated the area between the indicated line and the walking path. Additionally, we measured completion time, which was the sum of all times taken

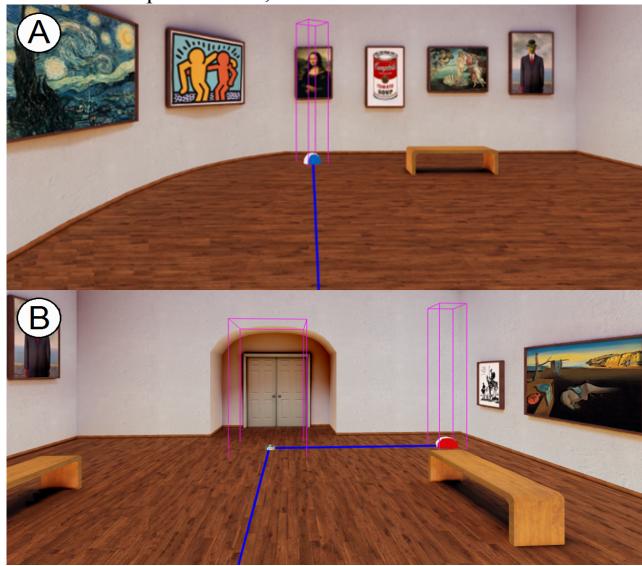


Figure 2 – User's view of the straight-line (A) and the multi-segment line (B) task. The ball on the floor represents the target.

to walk to the 12 targets in one task. Calibration time was excluded from the completion time. A post-questionnaire gathered subjective ratings about the three locomotion interfaces.

3.6 Participants

12 participants (10 males and 2 females) from the university undergraduate and graduate population were recruited on a voluntary basis for our study. The participants ranged in age from 18 to 35 years. We excluded subjects under the age of 18 and people with weight over 190 lbs (the weight limit of the Virtusphere). None of the participants had prior experience with the Virtusphere before the experiment.

3.7 Procedure

We received approval from the university's Institutional Review Board for our study. Upon arrival, participants were asked to read and sign an informed consent form. They next completed a background questionnaire that asked for their age, gender, occupation, eyesight, and experience of playing video games. After that they were given an introduction to our experiment background, facilities to be used, study procedures and locomotion interfaces. Participants had a short training session before using each locomotion interface, in which they were introduced to the 3D environment and were asked to perform a simple straight-line locomotion task.

For each locomotion interface, after completing the training session, participants were asked to perform three tasks through a 3D virtual model of an art gallery. The first two tasks were straight-line tasks and the last was a multi-segment line task. The same tasks were performed in all three locomotion interfaces to maintain consistency. We divided the 12 participants into three groups, and each group used a different ordering of the locomotion interfaces, based on a Latin square. After completing the tasks with each locomotion interface, participants filled out an interface questionnaire, using a seven-point Likert scale to measure their opinions regarding fatigue, ease of walking, ease of learning, naturalness, fun, and precision. Each interface questionnaire was followed by a simulator sickness questionnaire.

4 RESULTS

In this section, statistically significant results in our study are reported. The deviation and time metrics in our study were numeric continuous type, while all other subjective dependent variables in the questionnaires were numeric ordinal type. Our primary analyses were one-way analyses of variance (ANOVAs) for the time metric and the deviation metric.

4.1 Deviation

We used the deviation measure to evaluate task performance accuracy. We observed a significant effect of locomotion interface on the performance accuracy for both the straight line task ($F_{2,69}=35.10$; $p<0.0001$) and the multi-segment line task ($F_{2,33}=12.17$; $p<0.0001$), as shown in Figure 3. Pairwise comparisons using the Student's t-test showed that participants performed significantly less precisely using the Virtusphere, compared to real walking and gamepad techniques ($p<0.0001$ in both cases). No significant differences between the real walking and gamepad techniques were observed. In addition to the total deviation measure, we measured average and maximum deviation from the indicated line and total travel distance. The statistical analysis results were the same as for the total deviation measure.

4.2 Completion Time

We also found a significant effect of locomotion interface on the speed of the straight-line task ($F_{2,69}=77.41$; $p<0.0001$) and the

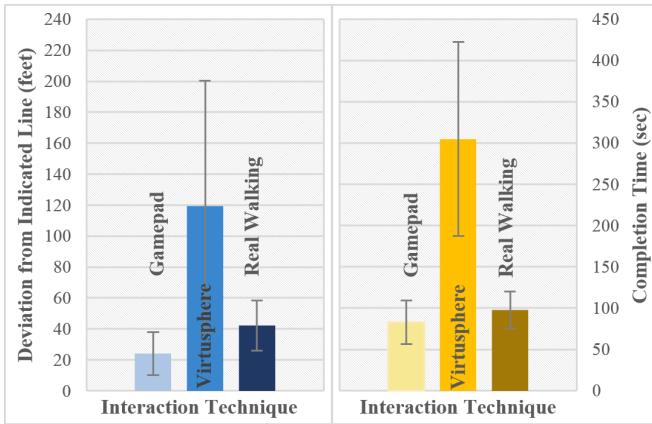


Figure 3 – Performance measures for the three locomotion techniques. A) Total deviation and B) Total completion time, for the straight-line task. Error bars represent standard deviation. multi-segment line task ($F_{2,33}=23.24$, $p<0.0001$), as shown in Figure 3. Pairwise comparisons using a Student's t-test indicate that participants performed significantly faster using the real walking and gamepad techniques as compared to the Virtusphere ($p<0.0001$ in all cases). No significant differences between real walking and gamepad interfaces were observed.

4.3 Questionnaire Results

We ran a Chi-Square analysis to compare the subjective ratings given in the post questionnaire. Participants felt that both the gamepad ($\chi^2_6=15.59$; $p=0.02$) and real walking techniques ($\chi^2_6=17.45$; $p=0.01$) were significantly easier to learn than the Virtusphere. Similarly, users found the Virtusphere significantly more fatiguing than real walking ($\chi^2_5=15.99$; $p<0.01$) and gamepad ($\chi^2_5=21.22$; $p=0.01$) techniques. Mean values are shown in Figure 4. We also asked users about their subjective opinion of each technique being fun, and despite the Virtusphere having a higher mean rating than the gamepad technique, we did not observe any significant differences for this question.

Users felt the Virtusphere was significantly more natural than the gamepad technique ($\chi^2_6=13.36$; $p=0.04$) and less natural than the real walking technique ($\chi^2_6=15.99$; $p=0.01$). Users perceived the gamepad to enable easier walking ($\chi^2_6=12.68$; $p<0.05$), initiation ($\chi^2_6=19.35$; $p<0.01$), and termination ($\chi^2_5=19.95$; $p<0.01$) than the Virtusphere. However, perceived precision and ease of walking were not significantly different when comparing real walking and the Virtusphere for “steady state” walking (i.e., once walking has begun, users do not perceive the Virtusphere to be significantly less precise or harder to use). These results are reflected in our interaction fidelity analysis (section 5).

4.4 Movement Patterns

Besides speed and accuracy, a higher fidelity locomotion interface should result in more realistic walking patterns [8]. We recorded

each participant’s position in the VE while performing the tasks and used this data to illustrate movement patterns, as depicted in Figure 5. For each interface, a representative pattern is indicated using a red dotted line. As participants reached a target in VE, they turned around looking for the next target. Using the real walking technique, participants usually started walking as they were looking for the next target. Therefore, as can be seen in Figure 5, the movement pattern is more deviated at the beginning of walking. The user could rectify his movement gradually while walking toward the target.

The movement patterns with the gamepad technique are similar to the real walking technique, although there are some distinctives. It is easy to move in a straight line with the gamepad technique, but if the straight line is not going exactly in the right direction, then the user will correct his direction, which creates a jagged movement pattern. Despite this, the user can still keep close to his desired path. The movement patterns with the Virtusphere are nothing like the movement patterns in real-world walking. The user often was not able to initiate the walk in the preferred direction. In addition, some participants could not hit the target at first and instead walked around it.

4.5 Results Summary

As we hypothesized, the Virtusphere was outperformed significantly by both the gamepad and real walking interfaces, indicating that it is slower, less precise, harder to use, more fatiguing, and more difficult to control. But why is this the case? Is the Virtusphere simply too novel and unfamiliar to users, or are there more fundamental issues with this locomotion technique and others like it? To address this question, we performed a detailed analysis of the differences among the three techniques.

5 ANALYSIS OF LOCOMOTION TECHNIQUES

McMahan introduced the Framework for Interaction Fidelity Analysis (FIFA) [18]. FIFA allows us to compare interaction techniques and where they fall on the fidelity spectrum. We employ FIFA to better understand differences among the three locomotion interfaces in our study. FIFA describes interaction fidelity with three primary factors.

Biomechanical symmetry describes the degree of correspondence between the body movements used in the interaction technique and the body movements used while performing the same task in the real world. Sub-components of biomechanical symmetry include kinematic, kinetic, and anthropometric symmetry. Kinematics is concerned with body motions or trajectories; kinetics refers to the forces applied to cause body movements; and anthropometry considers which body parts are used.

Control symmetry describes how the control provided through the interaction technique compares to control in the real-world task. It also has three sub-components: dimensional, transfer function, and termination symmetry. Dimensional symmetry

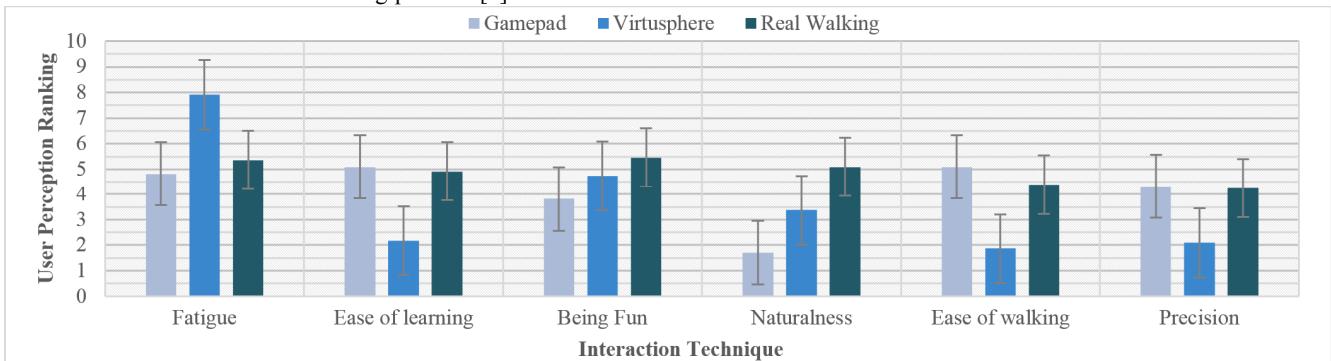


Figure 4 - Mean values for users' subjective ratings. Error bars represent standard deviation.

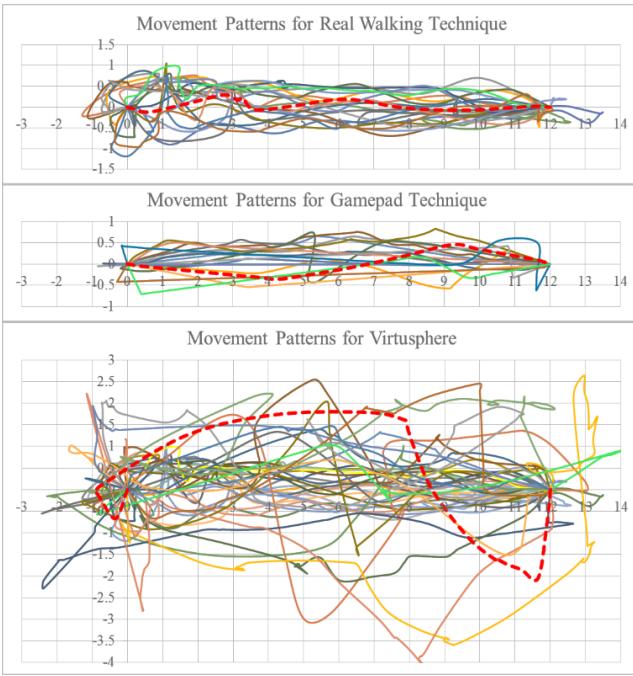


Figure 5 - Walking patterns for several walking tasks using real walking, Virtusphere and gamepad interfaces. A representative pattern is indicated with red dotted line. Units are in feet.

considers the similarity between the control dimensions in a real-world task and those in an interaction technique. Transfer function symmetry refers to how interaction techniques interpret and transform input data into an output effect. Termination symmetry is concerned with how the interaction is stopped (although not included in the original FIFA publication, we also consider initiation—how the interaction is begun).

System appropriateness characterizes the suitability of the system for performing a particular aspect of the interaction, and includes four factors: input accuracy, input precision, latency, and form factor.

The following sections present a FIFA analysis of the three techniques, beginning with a description of the baseline to which the techniques will be compared: natural walking.

5.1 Natural Human Walking

The most common force applied to the human body during walking is the ground reaction force. This force is a three-dimensional vector comprising a vertical component and two shear components. The two shear components act on the ground surface in anterior-posterior and medial-lateral directions [27], as shown in Figure 6A and B.

The human gait cycle has two main phases: the stance phase (60% of total time), in which the foot is in contact with the ground, and the swing phase (40% of total time), in which the foot moves forward in the air. During the stance phase, the foot exchanges forces with the ground. The stance phase is subdivided into heel-strike, foot-flat and toe push-off [25]. In heel-strike, the human foot (H) contacts the ground and exerts two elements of force in forward (H_x) and downward (H_y) directions into the ground (Figure 6B). The ground reacts with the same amount of force in the opposite direction (G_x , G_y) to the foot. Heel-strike continues with foot-flat in which the whole sole meets the ground and applies forces in the backward direction. Foot-flat changes into push-off, in which the foot exerts the largest backward force in the gait to translate the body forward (Figure 6A). The ground reacts with the same amount of force in the opposite direction.

5.2 Analysis of Real Walking Technique

Using a real walking interaction technique, users can translate and rotate in a tracked physical space while viewing the VE through a tracked HMD. In this technique, all translation and rotation scales are the same as the real world, and no gains are applied to the user's movements.

The real walking technique is extremely high fidelity. During the initiation, continuation, and termination of walking, all aspects of biomechanical symmetry and control symmetry are exactly as they are in natural walking. The only notable distinction between our real walking technique and natural walking is that the user is unable to observe her own body, legs, and feet while wearing the HMD, which might cause lower confidence in walking, leading to slower walking speed.

5.3 Analysis of Virtusphere Technique

5.3.1 Initiation

In natural walking we initiate the gait with the push-off phase. Because of the Virtusphere's inertia and static friction, as the user takes the first step or two, the Virtusphere may remain stationary (Figure 6C) and react with the same force in the opposite direction to user (GV). As the user moves forward, because of the curved inner surface, the user's downward force increases and overcomes the Virtusphere's static friction and inertia. As soon as the Virtusphere starts spinning (Figure 6D), the static friction turns into dynamic friction, which is less than static friction. This decrease in friction force reduces the amount of resistance against the force applied by the user's feet. An element of this force acts to overcome the dynamic friction, while the rest increases the Virtusphere's momentum, creating two elements of force in backward and downward directions on the user's feet (V_x and V_y in Figure 6D). This will decrease the Virtusphere's ground reaction force in forward direction (GVx) and downward direction (GVy). Consequently, the user will suddenly begin to move backward in the Virtusphere.

Users who are not acclimated to the Virtusphere have two typical reactions to the sudden backward movement. In the first scenario, the user will race to maintain her position while increasing walking speed, which will increase the Virtusphere's velocity and momentum. Then the user tries to slow down, but the Virtusphere's backward forces will translate her further backward. This can create a cycle, which ends up with the user losing her balance. In the second scenario, instead of racing, the user will try to slow the Virtusphere down. Inexperienced users might terminate Virtusphere's spinning and try to start over again. To avoid these two ineffective approaches, after the Virtusphere starts spinning, the user needs to gently slow the Virtusphere down and keep it spinning at a convenient speed.

This large difference in vertical and shear ground forces in the walking initiation phase causes a low kinetic symmetry between the Virtusphere and natural walking. This results in deviation from the indicated path and makes the Virtusphere more fatiguing and less precise.

5.3.2 Walking

As shown in Figure 6B, while the user is walking in the Virtusphere its momentum will exert backward and downward forces on the feet. During the heel-strike phase, this force increases the reaction force in the forward direction. Maintaining a constant speed while walking in the forward direction will create a balance between human forces and reaction forces. This balance makes linear walking in the Virtusphere almost natural. Because of the curved surface of the Virtusphere, if the user takes large steps, she might notice the difference in height. Taking smaller steps not only will keep both feet at the same height but also will

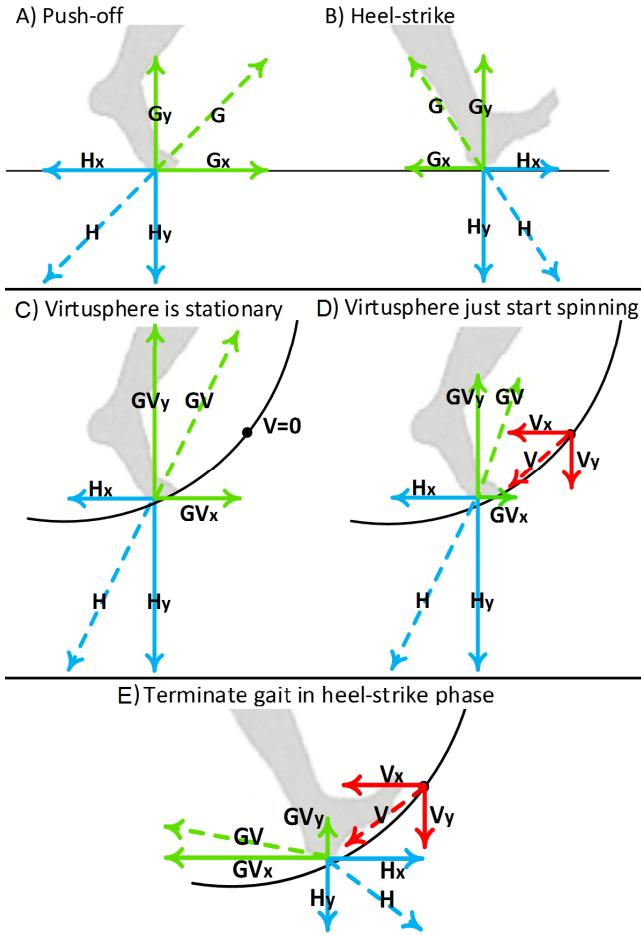


Figure 6 - Human foot forces (H) shown in blue, ground reaction forces (G) shown in green, Virtusphere forces (V) shown in red.

decrease the downward force element (Hy), which helps keep the Virtusphere's momentum in control. The precise input sensors can detect minor movements and have minimal latency. As a result, participants reported the Virtusphere to be more fun and natural compared to the gamepad technique.

5.3.3 Termination

In natural walking, we terminate the gait in the heel-strike phase. As the user tries to stop the Virtusphere, she needs to overcome the Virtusphere's momentum by exerting a larger forward force in the heel-strike phase. Inexperienced users might end up with two walking termination scenarios. In the first scenario, the user applies a larger forward force in the heel-strike phase, while reducing the backward force in the push-off phase, similar to natural walking. In this case, the Virtusphere's momentum translates the user backward and upward on its inner curve. Subsequently, the user increases the push-off force to go forward to maintain her position and control her balance. This can cause the user to move backward and forward several times, and eventually lose balance.

In the second scenario, the user applies a heel-strike forward force considerably larger than that of natural walking, to overcome the Virtusphere's momentum (Figure 6E). The Virtusphere's weight (550lbs [12]) can create a large momentum. Due to its momentum, the reaction force from the Virtusphere to the user's foot is relatively large and the user's muscles might not be able to overcome this reaction force (GV_x , Figure 6E). This can also cause the user to lose balance. Experienced users will gradually increase forward force in the heel-strike phase while gradually reducing backward force in the push-off phase to

terminate gait and maintain balance. Even in this case, termination is considerably different than natural walking. Thus, kinetic symmetry and termination symmetry are low-fidelity in the Virtusphere. These actions consume a considerable amount of energy if they are done over a long period of time, helping to explain the significantly higher reported fatigue with the Virtusphere in our study.

5.4 Analysis of Gamepad Technique

In the gamepad technique, walking is initiated by pushing the translation joystick forward, which causes forward movement in the VE almost immediately. The user can keep walking in VE by continuing to push the translation joystick forward, while he can strafe by pushing the translation joystick right and left. The user is able to control translation with high accuracy and precision. Termination of walking simply requires releasing the joystick.

The gamepad technique has high accuracy and precision, low latency, and high dimensional symmetry. In terms of interaction fidelity, biomechanical and control symmetry are very low. Different body parts are used, and movements and forces are entirely different. Transfer function symmetry is low, since tilting a joystick is mapped to velocity in the VE. Termination and form factor are also low-fidelity.

The lack of interaction fidelity is not an issue for techniques of this sort, since this technique is not designed to approximate real walking in any way.

5.5 Analysis Summary

We can see that the real walking technique has high interaction fidelity as it satisfies all three symmetry conditions for high-fidelity. Conversely, the gamepad technique has very low biomechanical symmetry, transfer function and termination symmetry and a very different form factor. Hence, the gamepad technique is near the low extreme of the interaction fidelity spectrum. The Virtusphere has a combination of both high-fidelity and low-fidelity properties. Considering this, we classify the Virtusphere as a medium-fidelity technique. This analysis also helps to explain the results of our study.

6 DISCUSSION

6.1 This experiment

In our experiment, the Virtusphere had significantly worse performance than the gamepad and real walking techniques, indicating that it is difficult to learn and use. The analysis described above helps us to understand the source of these usability problems. The Virtusphere presents itself as a "natural walking interface," implying to users that they can use their real-world walking skills and experiences to use the device. However, it turns out that initiating and terminating walking (not to mention changing direction) are significantly different, in terms of motions and forces, in the Virtusphere than in real walking. These differences cause users to struggle to control the Virtusphere and to be unable to walk proficiently along the desired path in the VE. The Virtusphere not only produced inferior performance in our study, but it made the walking behavior significantly different than real-world walking.

In contrast, the real walking technique has none of these issues. Users are able to transfer all of their real-world walking experience and skills directly to the interface, resulting in excellent performance.

But if the Virtusphere has inferior performance because of its deficiencies in fidelity, why does the low-fidelity gamepad technique not perform even worse? Clearly, users of the gamepad technique do not expect the technique to be like real-world walking, and thus the low-fidelity aspects of the interface are not a

hindrance to good performance. Instead, because the gamepad technique is well designed, with an easily understandable mapping between joystick movements and translational/rotational velocity, performance can be on par with real walking, at least for the metrics of speed and accuracy on a straight-line walking task.

Another advantage for the gamepad technique is familiarity. Many users have seen and used this type of interface often in games and other contexts. Certainly, familiarity does have an influence on performance. But was it a primary factor in the results of our experiment?

Three of our participants claimed that they played video games less than one hour per week, and that they used devices very different from gamepads (e.g. smartphones). Thus, these participants were novices in using techniques similar to the gamepad navigation technique. Their mean completion time was 105.3 seconds using the gamepad, compared to 262.0 seconds using the Virtusphere. The deviation with the gamepad technique for this group of participants was 19.1 feet, while it was 82.0 feet when using the Virtusphere. Therefore, even participants who claimed a low level of expertise with gamepad-like techniques could navigate much faster and more accurately with the gamepad than with the Virtusphere. This suggests that the gamepad technique we used was very easy to learn and use, enabling users to obtain excellent task performance even without prior training or high level of expertise with such a device.

One might also claim that the choice of experimental task affected the results. Based on our experience, walking in a straight line gives the Virtusphere the best chance of success. Due to the Virtusphere's momentum, walking on curved paths is more challenging. While it is true that the gamepad technique might be less optimal for non-straight-line movements, it will still greatly outperform the Virtusphere. In our experiment, therefore, we conclude that:

1. The high interaction fidelity of the real walking technique led to a high level of performance.
2. The medium fidelity of the Virtusphere technique (i.e., its deficiencies in fidelity compared to real-world walking), combined with user expectations that it would support natural walking, led to significantly worse performance.
3. The low interaction fidelity of the gamepad technique was not detrimental to performance, due to its easy-to-learn and easy-to-use design.

Of course, we were only able to evaluate three specific locomotion techniques in this study. We must ask ourselves whether these results are generalizable.

6.2 Implications

McMahan et al. hypothesized that high- and low-fidelity locomotion techniques often perform better than medium-fidelity ones [17,18]. In other words, he argued that the relationship between interaction fidelity and performance might look like a U-shaped curve, with higher performance at the two extremes and lower performance in the middle. Our results support this hypothesis. We observed that increasing fidelity from a low-fidelity standard technique (gamepad) to a medium-fidelity technique (Virtusphere) decreased performance and that increasing from medium-fidelity to highly natural (real walking) contributed positively to performance.

This hypothesis is sensible because medium-fidelity techniques appear similar to high-fidelity interactions. Therefore, users try to employ them in a similar way to highly natural techniques. Nevertheless, due to their differences from real-world actions, medium-fidelity techniques require users to change the way they naturally interact. The brain must adapt to the non-natural parts of the medium-fidelity technique.

Despite all of the efforts to develop more-natural locomotion interfaces (such as omni-directional treadmills, walking in place, and robotic stepping systems), these and most other practical locomotion interfaces lie in the middle of fidelity spectrum. So it is important to understand the potential performance of this category of locomotion interfaces.

One might argue that the results in our study could be due primarily to the particular medium-fidelity interface we chose (the Virtusphere). While we acknowledge that the Virtusphere has some clear deficiencies (in particular, its weight and curved shape), we hypothesize that these findings are valid for most medium-fidelity locomotion techniques to some degree. This conclusion may also be true for other interaction tasks besides locomotion, but further study is required.

Our results are consistent with other studies showing the inferior performance of semi-natural interfaces in the literature [14,16,17] (see section 2 for a description of these studies).

On the other hand, some studies have revealed high levels of performance for certain semi-natural techniques, such as redirected walking [21] or seven league boots [11]. Based on an analysis similar to the one in section 5, we can see that these techniques are actually quite high fidelity in terms of the muscle groups and forces they use; thus they have high biomechanical symmetry. The transfer function for both of these techniques is slightly different than natural walking. With redirected walking, the user might not even notice the difference with real walking. The gain used in seven league boots can be perceptible for the user, nonetheless it is in favor of navigation speed and performance. Therefore, such techniques are close to the high extreme in the interaction fidelity spectrum, and their good performance does not contradict McMahan's hypothesis.

The effects of familiarity are not independent of the effects of interaction fidelity. By definition, a technique with high interaction fidelity is highly familiar, since a high-fidelity technique is very similar (familiar) to the actions used in the real world. Also by definition, a technique with low interaction fidelity is completely unfamiliar until users have trained with it or used it for a while. Medium-fidelity techniques are by definition somewhat familiar.

Nevertheless, this is the main problem with the Virtusphere: Since it presents itself as a *natural* walking technique, users assume that regular walking motions and skills will apply to it. When they try to use regular walking in the Virtusphere, they have great trouble. Therefore, *familiarity* is actually a downside of the Virtusphere, and its closeness to natural walking is more of a distraction for the user than an advantage.

The primary reason why low-fidelity techniques *may* perform well is not familiarity; it's that they can be well designed, using established principles of human-computer interaction. Because these techniques are not based on real-world actions, designers are free to invent techniques that will perform well. Certainly, *low fidelity does not guarantee good performance*, but well-designed low fidelity techniques can have excellent performance.

Users' performance with medium-fidelity techniques need not always remain low. It is possible to improve performance by training users [13]. However, if an interface requires extensive training to be usable, it is not likely to be appropriate for many potential applications. Moreover, the need for significant training with a technique runs counter to the idea of "natural" interaction. How much and how quickly the performance of medium-fidelity techniques can be improved is a topic for future work.

In summary, based on the literature, our results, and our deep analysis of interaction techniques, we suggest that McMahan's hypothesis has merit, at least for basic task performance measures with locomotion techniques. That is, high-fidelity locomotion techniques and well-designed low-fidelity locomotion techniques

will often outperform their medium-fidelity counterparts. Further studies can reinforce this premise.

7 CONCLUSIONS AND FUTURE WORK

Despite the common belief that more realism in VR systems is always better, we have demonstrated that the relationship between interaction fidelity and effectiveness is more complicated. By analyzing and evaluating three locomotion interfaces at different points on the interaction fidelity spectrum, we have contributed a deeper understanding of the effects of interaction fidelity on effectiveness.

Based on the literature [14,16-18] and our results and analysis, we suggest that high-fidelity locomotion techniques and well-designed low-fidelity techniques can outperform medium-fidelity locomotion interfaces. Our results support McMahan's hypothesis [17,18] about the interaction fidelity-performance relationship. More studies are required to strengthen this hypothesis with other medium-fidelity locomotion interfaces and techniques for other tasks.

In the future we can extend this research to further study the shape of the interaction fidelity-performance curve. More interaction techniques can be studied to address the question of how much fidelity is needed to achieve performance similar to the real world, or which components of interaction fidelity are most important to have at high levels.

We also plan to further investigate how to improve the level of effectiveness of medium-fidelity VR techniques. For example, with the Virtusphere, one could decrease its mass, lower the static friction, provide a more appropriate level of dynamic friction (perhaps with mechanical assistance), and train users on simple strategies to walk more proficiently in the device.

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