New simple virtual walking method – walking on the spot

L. Yan, R.S. Allison

York University, 4700 Keele St., Toronto, Ontario, Canada, M3J 1P3

S.K. Rushton

Cardiff University, PO Box 901, Cardiff, CF10 3YG, UK

allison@cs.yorku.ca, *cs213449@cs.yorku.ca*, *RushtonSK@cardiff.ac.uk*

Abstract

In CAVE-like environments human locomotion is significantly restricted due to physical space and configural constraints. Interaction techniques based upon stepping in place have been suggested as a way to simulate long range locomotion. We describe a new method for step detection and estimation of forward walking speed and direction in an immersive virtual environment. To calibrate our system and to help in the modeling of the stepping behaviour, we collected motion capture data during real locomotion down a hallway while walking at different freely selected speeds, from very slow to very fast. From this data, the empirical relation between the forward speed of real walking and the trajectory of the leg motion during stepping was established. A simple model of stepping motion was fit for individual subjects. The model was used to estimate forward walking speed and direction from step characteristics during walking in place in a six-walled virtual environment. The system provides natural and effective simulated gait for interaction and travel within the virtual environment and provides the ability to study human locomotion and navigation in a CAVE-like environment.

Key words: virtual environment, locomotion, human-computer interaction, walking in place

1. Introduction and Motivation

Presentation of effective virtual environments in CAVEs, and other projector-based systems with fixed display surfaces, depends on the user being located near and looking at the screens. Tracking systems typically also restrict the range of user motion. In a six-walled CAVE the user is completely enclosed and the motion is necessarily restricted to the volume of the physical environment. Thus, a key issue in the design of virtual environments has been the provision of means to virtually travel beyond the physical constraints of the display system.

A number of researchers have addressed issues related to human navigation and travel in VE. The most common method of movement in CAVEs is to fly using an interface device such as a joystick [1]. This hand-based steering and motion control leads conflict with other hand-based manipulation and relies on the subject continually pointing the device in the direction of travel. Furthermore, if locomotion is simulated the interaction is not natural and the visual motion conflicts with other sensory information (for example from the vestibular system and proprioception), which indicates that the user is not physically moving.

Another common method of travel for simulated human locomotion is the treadmill. The earliest locomotion system using a treadmill was a unidirectional system [2]. Later, multidirectional systems such as the Omni-Directional Treadmill were developed [3]. An individual walking on the surface of the Omni-Directional Treadmill can move in any direction, and the device actively maintains the user's position at the device center. These platforms require the user to make natural limb motions during walking and other types of simulated locomotion. Thus, they provide for natural proprioceptive and active movement cues to motion through the virtual environment. However, they have several disadvantages. They tend to be large and physically intrusive which can interfere with immersion. In one system, the Cybersphere (http://www.vr-systems.ndtilda.co.uk/sphere1.htm) the projection surface is a large sphere that can turn as a treadmill. One problem with treadmill systems is that they have significant inertia and starting and stopping the motion of the treadmill can take additional effort and require that non-realistic forces be exerted by the legs.

A simpler, less intrusive solution is to have users walk in place and control the movement of the user through the virtual environment by their stepping rate.

The system described by Slater [4] used a neural network based on head tracker data to distinguish walking in place from other movements in the virtual environment. They reported that this works reliably even without customization for individual gaits. During natural locomotion the head moves significantly during each stride. However, during walking in place the extent of head motion is considerably smaller unless the walking is quite animated. For this reason we used tracking of the legs rather than only the head.

Templeman developed a virtual locomotion interface, called Gaiter, for military simulators [5]. The motion of legs was detected by force sensors placed on shoe insoles, and six-DOF trackers attached to the knees sensed the distance and direction of leg motion. The system was quite flexible and could detect a variety of locomotion types important for military operations. However detection of a step during forward motion required waiting for the knee to swing forward and reverse. This adds unacceptable latency for our application. The provision for a large variety of movement types (such as gestural side-stepping), which are irrelevant for simple forward stepping along a straight or curved path is not required for our studies of human locomotion.

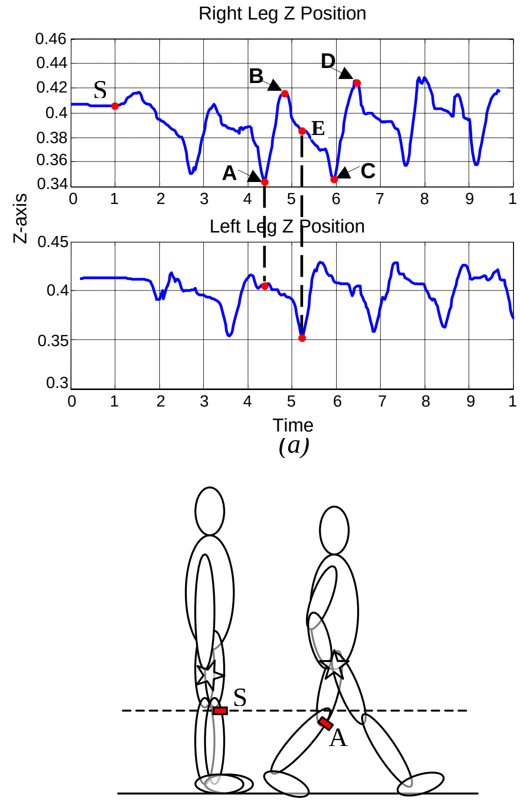
For our work, we needed to develop a reliable, low latency, efficient virtual walking method that supported simulated forward motion linked to stepping and turning in place. Once sustained forward locomotion is achieved, smoothing and predictive techniques can generate smooth simulated motion. However, for our experiments we needed to simulate realistic forward motion when the user took a step from a standing position. Hence latency is a key issue and we traded the flexibility of Templeman's approach for a more responsive system.

Biomechanics research shows that humans tend to choose a step length or step frequency that minimizes metabolic energy consumption at a given walking speed [6]. The speed an individual walks (v) is the product of step length (d) and step frequency (f). Terrier and Schutz [7] showed that there is a constant ratio between step length and step frequency over a large range of walking speeds. In other words, for a particular user, at a given walking speed, the step length and step frequency is constant. Energetic considerations and stability constraints are believed to underlie these phenomena [8].

The purpose of the present study was to explore the inter-subject variability of gait characteristics, specifically the leg lifting speed while walking at different freely selected forward speeds, from very slow to very fast. The result was used to predict virtual walking speed during walking in place in a VE. The method provides a simple efficient virtual walking method that supports forward stepping and torso based steering in a VE.

2. Analysis

The typical example of the time course of the vertical position of the leg (upper calf) during normal forward walking is shown in Figure 1(a).



(b)

Figure 1. (a)Vertical position of a sensor mounted on the back of a subject's calf as a function of time. The step is initiated at point A with the beginning of the stride for the Right Leg. The stride for the right leg ends at point E. (b)Points S, A correspond to the leg position S, A in Figure 1a.

The step began at point A while the right foot was at rest on the ground. Point A corresponds to the lowest position of the right leg and as the step began the right leg started to lift up (Figure 1(b)). At point E the left leg started its stride. So, we set point E as the end of the right leg stride. During normal locomotion the vertical rise and fall of the leg is associated with forward displacement of the leg and body. In walking in place, the leg moves initially forward and then reverses and returns. In both cases, the leg rises and falls on each stride and the characteristics of this motion can be used to predict stepping rate and forward velocity.

From point A to point E, one stride can be divided into two phases: one has a strong rapid rise (increase in height of the leg, from A to B), and the other is a falling phase (from B to E). Typically, in the first phase of a stride (from A to B), the leg initially accelerated upwards strongly from zero speed. About midway between A and

B, the leg achieves maximum velocity and begins to decelerate eventually reversing direction at maximum height (point B). The leg returns to ground with a downward motion. For walking in place, this motion is approximately symmetrical with the upward motion (from B to E in Figure 2). A typical example of leg lifting speed while walking on the spot is shown in Figure 2.

For this study we used the strong initial acceleration of the leg to determine the leg lifting speed and predict the forward velocity. It was found that the initial lifting speed of the leg specifies a particular forward walking speed. We therefore applied an estimation algorithm to predict the velocity of forward walking based on the vertical movements of the legs while walking on the spot.

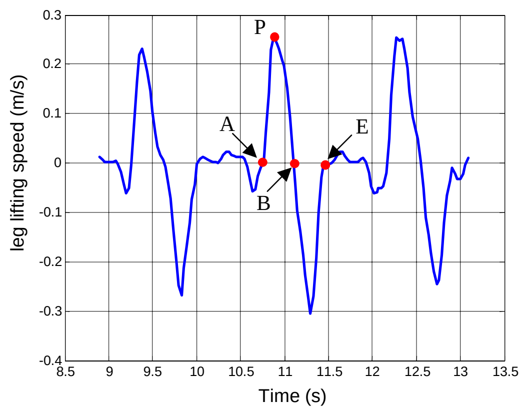


Figure 2. The leg lifting speed against time while walking on the spot. The leg lifting speed from point A (0 m/s) to point E (0 m/s) during a stride. Points of zero velocity A, B, E correspond to position features A, B, E during real walking in Figure 1(a). Point P is the maximum speed following the strongly accelerating phase.

For this estimation we needed an empirical model that related the leg lifting speed (v_l), step frequency (f) and forward walking speed (v) for real walking. The hypothesis was that leg lifting speed was related to step rate and that forward walking speed was a function of stepping rate over the range of speeds of interest. In particular, we assumed that $v = g(v_l)$, where g is an approximately linear relation and that $v_l = h(f)$, where h is also an approximately linear relation. We also needed to study how leg lifting speed (v_{ls}) (note: subscript s indicates walking on the spot) varies with different step frequencies (f_s) while walking on the spot. The hypothesis was that $f_s = k(v_{ls})$, where k is a linear relation.

When real walking and walking on the spot have the same frequency ($f = f_s$), we assume that the virtual walking in virtual environment (VE) should have the equivalent forward velocity as real walking at the same step rate ($v = g(h(k(v_{ls})))$). So, during real time interaction in the VE, we can use speed of leg lifting to determine forward velocity of body. In practice, users felt that this resulted in comfortable and natural simulated walking when traveling through a VE.

Recent studies have demonstrated that forward speed and vertical motion of the body during forward locomotion have a strong correlation but that the slope of the relation varied among subjects [9,10]. We decided to individually calibrate each subject based on their natural walking behavior to obtain a relation between v and v_{ls} tailored to each person's walking style.

3. Real Stepping Down a Hallway

The purpose of the hallway experiment was to explore the relationship between forward speed and leg lifting speed, in order to individually calibrate the predictor. The experiment consisted of two conditions: real walking and stepping in place.

3.1 Subject

Participants were recruited from York University. There were eleven subjects in total, of which two were females and nine were males. Participants ranged in age from 20 to 30; in weight from 51 kg to 83 kg with a mean weight of 63.5 kg; in height from 1.62 m to 1.83 m with a mean height of 1.73 m. Five participants had some previous experience with VE; the other six participants including the two females did not have any previous experience with VE.

3.2 Material

Body motion was captured using an InterSense IS-900 Precision Motion Tracker. The system is a hybrid acoustic-inertial 6 DOF position and orientation tracking system. For the hallway experiments, we used an InterSense IS-900 configuration with 3 sensors and 4

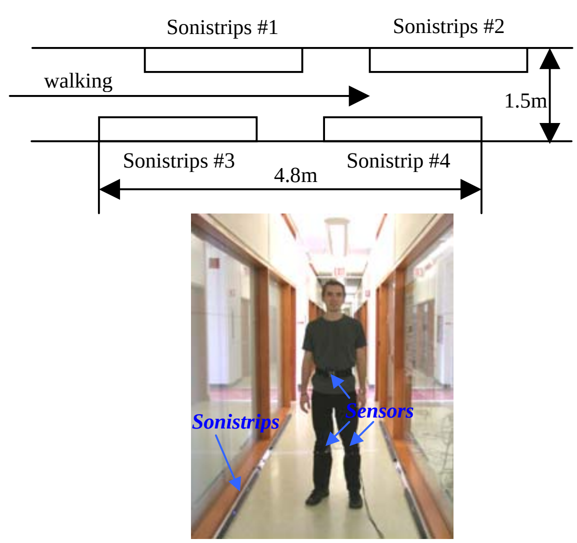


Figure 3. Mounted InterSense IS-900 in the hallway.

Sonistrips. Two Sonistrips were put on one side of the hallway, and the other two were put on the other side of the hallway (straight hallway continuing well beyond either end of the test area). One sensor (tracked device) was put on the subject's abdomen, and the other two sensors were put just below each knee (Figure 3). Using these three sensors we recorded three-dimensional subject motion at a sampling rate of 50Hz.

3.32 Experiment and Result

Before the experiment, participants received a brief introduction about the Intersense tracking system, were given a demonstration of natural walking and walking in place by the experimenter, and also were shown the experimental environment. Then, all participants were asked to familiarize themselves with walking with equipment attached through the hallway. They were asked to walk at several different speeds covering their preferred range of walking speeds, from the lowest speed to the highest speed that they could perform easily.

In the first hallway sub-experiment, subjects were asked to freely walk ten times in the hallway. The purpose was to give maximal freedom to the subject in selecting ten different self-selected walking speeds over a large range of walking speeds. Hence, the instructions were to walk at a very slow walking speed during the first trail, and to increase the walking speed for each subsequent trial. For each trail the subject was instructed to maintain a consistent speed of walking. This experiment demonstrated the relation of the speed of leg lifting (v_l) to forward walking speed (v) (Figure 4), and the relation of

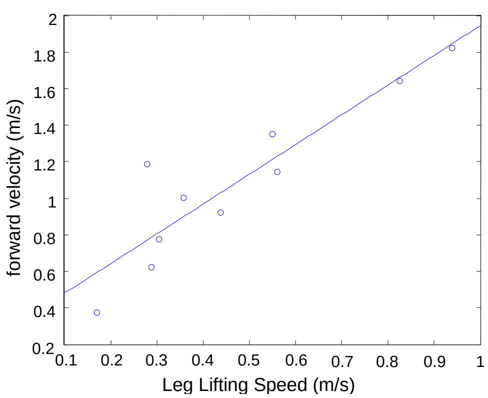


Figure 4. An example of the forward velocity of a subject's body versus leg lifting speed during real locomotion down the hallway. Straight Line Fit: $v=1.63v_l + 0.32$.

the speed of leg lifting (v_l) to step frequency (Figure 5). The speed of leg lifting was estimated using a 5-point differentiator filter (-3dB bandwidth of 10Hz). In Figure 4-6, the leg lifting speed plotted corresponds to the average speed during the initial accelerating phase (e.g. from point A to P in Figure 2).

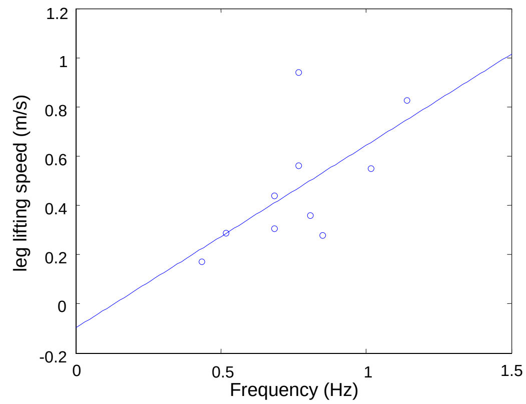


Figure 5. Step frequency versus the speed of leg lifting during real locomotion down the hallway for the subject in Figure 4. Straight line fit: $v_l = 0.74 f + 0.10$.

In the second hallway sub-experiment, subjects were asked to walk in place at ten different self-selected walking frequencies, ranging from very slow to very fast. The purpose of this experiment was to study how the in-place leg lifting speed (v_{ls}) varies with the in-place step frequency (f_s). The result is shown in Figure 6.

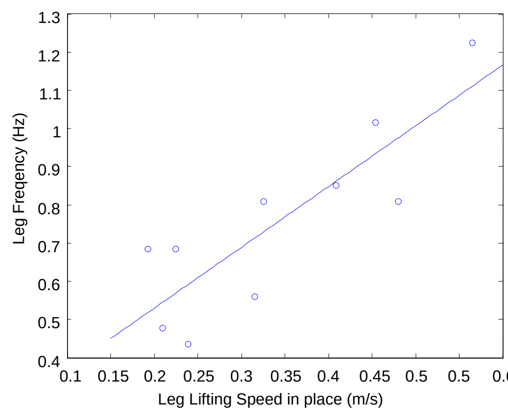


Figure 6. Walking in place step frequency versus the speed of leg lifting for the subject in Figure 4. Straight Line Fit: $f_s=1.59v_{ls} + 0.21$.

From these three relations for this particular subject's data, we can model the relation between leg lifting speed and simulated forward velocity.

$v = 1.63\ v_l + 0.32$

$v_l = 0.74\ f + 0.10$

$f_s = 1.59\ v_{ls} + 0.21$

We conclude forward speed (v) = 1.92 * Speed of leg lifting (v_{ls}) + 0.57 for this subject.

As an example and sanity check, if we take the subject's mean leg lifting speed during walking on the spot (0.3 m/s) and follow the procedure above then we arrive at an estimated forward velocity of 1.15 m/s. This value closely approximates the average forward walking speed for this observer during real locomotion.

Similar relations between leg lifting speed during walking on the spot and forward velocity were found for each subject. Across all eleven subjects, the linear relationship had a mean slope of 2.09 (+/-0.69 SE) and a mean intercept of 0.49 (+/-0.14).

4. Our New Virtual Walking Model Algorithm

Virtual walking allows users to walk on the spot to move across virtual distances that are greater than the limited physical space. A tracking device is used to map real body movements to corresponding virtual movement in the VE. A simple model of the control of natural virtual walking can be divided into three parts: estimation of the direction of walking, the velocity of walking, and the viewport (since users may look around in the VE while walking in one direction.)

Figure 7 illustrates the methodology of our simple virtual walking technique. In this system four sensors are mounted on the user's body.

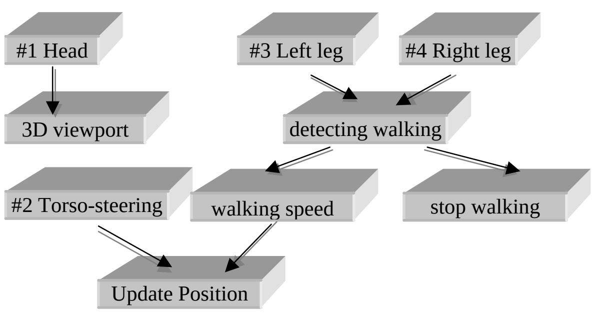


Figure 7. Overview of the approach used for detecting walking and predicting speed. Four InterSense sensors are used.

The first sensor is a head tracker which is mounted on user's head to control the viewport in 3D in the normal fashion. A second sensor is placed on the torso at the waist. This sensor is used for torso-based steering through the VE in response to stepping movements. Placement at the waist makes the system relatively insensitive to twisting motions of the torso and frees the upper body and head for looking about the VE. The third and fourth sensors are placed on the back of each leg just below the knee.

The first step of the leg-based algorithm is to deduce whether the person is walking or not. In our system, forward virtual motion is triggered when leg lifting speed is greater than a speed threshold.

Once a step is detected the system estimates the forward velocity of the body based upon the initial leg lifting speed and generates a step through the virtual environment. The forward velocity corresponding to the step is calculated from the relations measured for each individual subject. We used Kalman filtering to smooth the forward velocity estimates across individual steps.

The exact position of the user in the VE can be calculated at each simulation interval based on the current estimated forward velocity and torso orientation data which determines the step direction (from the torso-steering tracker.) Any real motion of the user or his head is sensed by the head tracker, added to the position based upon virtual stepping and used to generate the user's position for rendering the displays.

5. Validation in IVY

The accuracy and usability of the step detection and the speed prediction model were evaluated during an experiment in an immersive virtual environment.

The Immersive Visual environment at York University (IVY) is a 6-sided cube in which all of the walls of the cube are rear-projected video surfaces, including the ceiling and floor [11]. A picture of this Cave-like system is shown in Figure 8.

Figure 8. The Immersive Visual Environment (IVY) at York University (fish-eye view)

For these experiments, an InterSense IS-900 VWT tracking system was used to track the user's head, body and leg movements. The fixed frame containing the acoustic beacons was mounted in the doorway to IVY, blocking one wall and making IVY essentially a 5-walled environment for these experiments. One InterSense sensor was mounted on the subject's head; one sensor was mounted on the small of subject's back, and the other two sensors were mounted on the back of the right and left legs, just below the knees (see Figure 9). The experiment consisted of two simple demonstration conditions.

In the first condition the VE consisted of a blue sky, a flat ground plane with grass texture, and one static target initially positioned five meters from the center of the cube. All subjects were asked to walk to the target while counting the number of steps required.

In the second condition the virtual environment consisted of blue sky, a flat ground plane with grass texture, four textured cylindrical obstacles in certain positions, and one

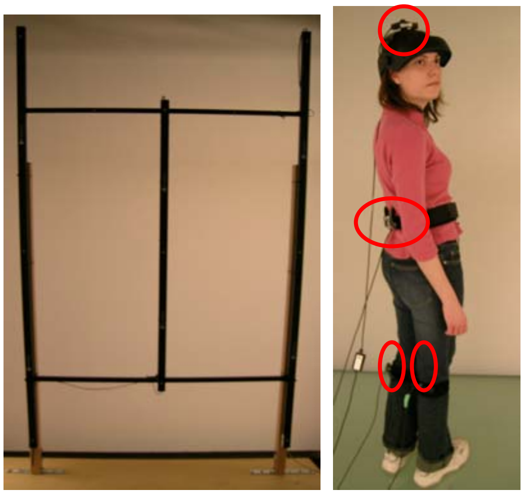


Figure 9. InterSense IS-900 in IVY. Ellipses show the sensors' placement.

moving target behind the farthest cylinder. All subjects were asked to zigzag around the cylinders to reach the target without colliding with the cylinders, and they were permitted to stop walking while orientating themselves during this experiment. Figure 10 is a screenshot of the VE. This required the system to detect and respond to the termination of the stepping behavior. The task was repeated two times.

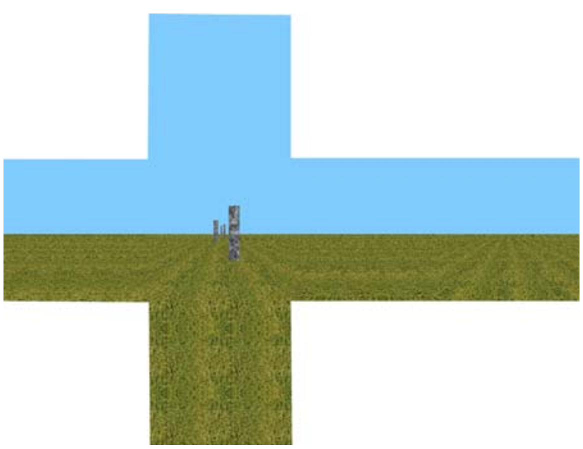


Figure 10. A screenshot of the virtual environment of experiments in IVY.

Prior to running the experiments, subjects were required to walk to a target 5 m away in the hallway at normal speed, and the number of steps taken was recorded. They were also asked if they had any previous experience with an immersive VE.

Following the full experiment, subjects were asked to evaluated the virtual walking control technique using a 1-to-5 response Likert scale (strongly disagree, disagree, undecided, agree, strongly agree) for 5 questions:

1. It was easy to control my direction of motion in the VE.
2. When I started lifting my legs, it felt like I was immediately moving forward in the VE.
3. When I stopped walking, it felt like my motion in the VE stopped appropriately.
4. While I was walking, my speed in the VE was consistent with my stepping.
5. Overall: walking in the VE is natural.

It was found that the number of steps required to walk to a static target was similar in real and virtual walking conditions. In both of these conditions, the number of steps required was around 7 ~ 9.

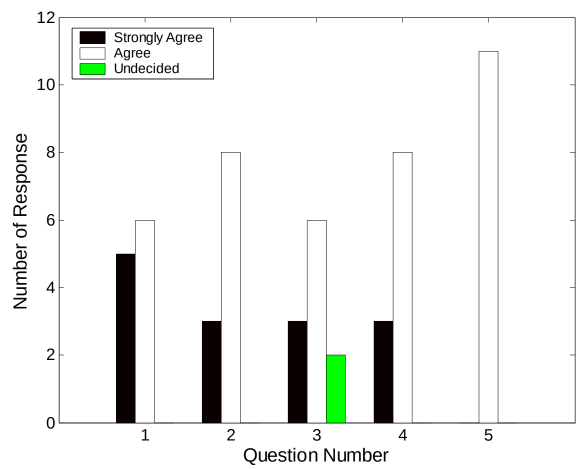


Figure 11. Summary of responses to the post-experiment questions. 1 – 5 are the question numbers as described in the text.

Figure 11 shows that all subjects agreed the motion in the VE was natural. No subjects responded that they disagreed or strongly disagreed for any of the statements on the survey. Subjects either agreed or strongly agreed that the control of direction, forward speed, starting and stopping behavior, and overall interaction was natural. During debriefing, subjects reported that the overall interaction was natural and consistent with real walking but not equivalent to real walking.

To test how sensitive people are to imprecision in the empirical parameters used in estimating walking speed, subjects were asked to repeat the IVY experiment using other subjects' empirical relations. We found that all of them felt that the motion in the VE was still natural as long as their estimated forward velocity remained within their preferred speed range.

Discussion

This paper describes the development and usability analysis of a new simple virtual walking technique that allows for realistic navigation through a virtual environment with low latency and without requiring exaggerated stepping motions. The technique is potentially useful for psychological experimentation, entertainment, and training applications in immersive virtual environments.

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