A Feedback-Controlled Interface for Treadmill Locomotion in Virtual Environments

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Virtual environments (VEs) allow safe, repeatable, and controlled evaluations of obstacle avoidance and navigation performance of people with visual impairments using visual aids. Proper simulation of mobility in a VE requires an interface, which allows subjects to set their walking pace. Using conventional treadmills, the subject can change their walking speed by pushing the tread with their feet, while leveraging handrails or ropes (self-propelled mode). We developed a feedback-controlled locomotion interface that allows the VE workstation to control the speed of the treadmill, based on the position of the user. The position and speed information is also used to implement automated safety measures, so that the treadmill can be halted in case of erratic behavior.

We compared the feedback-controlled to the self-propelled mode by using speed-matching tasks (follow a moving object or match the speed of an independently moving scene) to measure the efficacy of each mode in maintaining constant subject position, subject control of the treadmill, and subject pulse rates. In addition, we measured the perception of speed in the VE on each mode.

The feedback-controlled mode required less physical exertion than self-propelled. The average position of subjects on the feedback-controlled treadmill was always within a centimeter of the desired position. There was a smaller standard deviation in subject position when using the self-propelled mode than when using the feedback-controlled mode, but the difference averaged less than 6 cm across all subjects walking at a constant speed. Although all subjects underestimated the speed of an independently moving scene at higher speeds, their estimates were more accurate when using the feedback-controlled treadmill than the self-propelled.

Categories and Subject Descriptors: I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism—*Virtual reality*; I.3.4 [**Computer Graphics**]: Graphics Utilities—*Virtual device interfaces*; H.5.2 [**Information Interfaces**]: User Interfaces—*Evaluation / Methodology*

General Terms: Experimentation, Human Factors, Measurement

Additional Key Words and Phrases: Locomotion, low-vision, speed-matching, treadmill

ACM Reference Format:

Lichtenstein, L., Barabas, J., Woods, R. L., and Peli, E. 2007. A feedback-controlled interface for treadmill locomotion in virtual environments. ACM Trans. Appl. Percpt. 4, 1, Article 7 (January 2007), 17 pages. DOI = 10.1145/1227134.1227141 http://doi.acm.org/10.1145/1227134.1227141

This work was supported in part by NIH grant EY12890 to E. Peli.

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1. INTRODUCTION

Low-vision mobility aids are optical or electro-optical devices that provide people with visual impairment (low-vision) visual assistance during walking. The devices help their users navigate and identify potential obstacles [Gottlieb et al. 1992; Peli 2000a, 2000b]. People with visual impairment are frequently elderly, or have other health problems, which makes testing low-vision mobility aids in the real world difficult and potentially dangerous. Virtual environments (VEs) have great potential as test beds for low-vision aids by providing a safe, controlled environment that is repeatable and, thus, facilitates comparisons across conditions and between observers and devices. VEs also serve as excellent platforms to test spatial navigation (way finding) and collision detection and avoidance [Apfelbaum et al. 2006; Barabas et al. 2004a; Cutting et al. 1995; Fajen and Warren 2003; Foo et al. 2005; Loomis et al. 1992; Woods et al. 2005].

In many studies, subjects have been seated or standing still while they "walked" in the VE [Cutting et al. 1995, 2002; Li and Warren 2000; Wann et al. 2000]. Having the subject walk may improve the sense of presence (the subjective experience of being in the VE) and may make task performance more similar to the real world. Locomotion in a VE can be achieved by walking on a treadmill, usually viewing a fixed screen [Barabas et al. 2004a; Bardy et al. 1999; Durgin et al. 2005a, 2005b; Woods et al. 2003], or by walking freely in an open room while viewing a head-mounted display (HMD) [Chaudhury et al. 2004; Fajen and Warren 2003, 2004; Foo et al. 2005; Loomis 1992]. Free walking has many advantages, but few researchers have access to a sufficiently large open space, and costly equipment. Standard treadmills do not allow subject-controlled changes in speed or direction that may be required in studies of spatial navigation and collision avoidance. In most treadmill studies, the subject walks on the motorized treadmill at a speed or speeds set by the experimenter [Bardy et al. 1999; Durgin et al. 2005a, 2005b; Woods et al. 2005]. An alternative that allows subjects to vary walking speed is to use the treadmill without an active motor. Such self-propelled treadmill mode requires that the subject push the treads while using handrails or ropes to provide force to walk against [Apfelbaum et al. 2006; Distler et al. 1998; Thurrell et al. 1998; Woods et al. 2003]. While this may be acceptable for younger, physically fit subjects, older or less fit subjects may have difficulty with the level of exertion required to push the treadmill for the duration of a study session. Thus, data quality may degrade because of subject fatigue or the amount of data that can be acquired may be restricted.

Subject position on the treadmill cannot be specified easily with either fixed speed or self-propelled treadmill methods. For certain studies, the visual angle of the display should be constant during a session and across subjects. Maintaining a stable location on the treadmill with existing techniques requires careful manual measurements and physical restraint of the subject (e.g., tethers). Locomotion interfaces that attempt to simulate natural walking have been reported previously, but they were expensive for practical implementation (usually because they embodied features not needed for the experiments, such as rapid tilt for rough terrain simulation, split-belt walking, and support for running speeds) [Hollerbach et al. 2000; Iwata 1999a, 1999b; Prokop et al. 1997; Schubert et al. 2005], were unstable without subject training [Darken et al. 1997], or did not actually simulate walking [Iwata 1999a; Wells et al. 1996]. Hollerbach et al. [2000] reported a treadmill-based locomotion interface (Sarcos Treadport) that used a mechanical tether to center users as they walked or ran on a larger treadmill (305 cm length by 183 cm wide). In addition to centering the user, the mechanical tether applied inertial forces to give the subject a natural feeling during acceleration and deceleration. Minetti et al. [2003] reported a feedback-controlled locomotion interface (treadmill-on-demand) that was originally used for measuring walking and running speeds, rather than in a VE. The user's position on the treadmill was a function of speed and thus the controller varied the user's distance from a display. The slow response time of 420 ms of that system may not be sufficient to react safely if a subject falls.

Using a conventional exercise treadmill and easily acquired parts, we built a feedback-controlled treadmill locomotion interface that altered the speed of the treadmill motor to maintain a position sensor within a small region of our 164 by 55 cm treadmill, with a response time of less than 60 ms. This simple to use locomotion interface allowed subjects on the treadmill to vary their walking speed, to walk with no more exertion than natural walking, and to be repositioned automatically by the interface. We evaluated its performance by comparing it to the self-propelled treadmill mode, which also allows the user to dynamically adjust their speed and is relatively inexpensive to implement.

2. METHODS

2.1 Apparatus

Subjects walked on a Woodway Desmo S treadmill (http://www.woodway.com), which is similar to those commonly found in a gymnasium. The treadmill was modified to allow the VE computer to control the treadmill speed (see below). Self-propelled locomotion was also possible.

For self-propelled walking, subjects were anchored to a rope behind them, so that they could push the treadmill belt and keep from moving forward while walking. Subjects wore a safety harness, connected to the ceiling, for protection in case of a fall. As a second safety measure, subjects were attached to a front rail so that they could not slide off the back of the treadmill if they stopped walking while the treadmill belt continued to advance because of the incline of the treadmill. The operator was able to trigger an emergency brake during the feedback-controlled portion of the experiment (this was never necessary).

Our VE was generated on an Evans and Sutherland simFUSION 4000q workstation (http://www.es.com) and was displayed onto a Stewart Filmscreen Corporation (http://www.stewartfilm.com) rear-projection screen using an Epson Power lite 9100i (http://www.epson.com) projector running at 60 Hz. The average luminance was 57 cd/m^2. Display resolution was 1280 by 960 pixels and subjects could see the edge of the screen. The screen measured 172 by 127 cm, which provided 104° horizontal by 87° vertical field when the subject was 67 cm from the screen (the average head position for subjects doing the self-propelled portion of the experiment) and 91° by 75° at 84 cm (the average head position for the feedback-controlled portion). Head position varied because during the more strenuous self-propelled walk subjects tended to lean forward bracing against the taut rear tether.

A Flock of Birds Magnetic Tracker (http://www.ascension-tech.com) with two position sensors was used to monitor the subject's body and head positions at 60 Hz each. Measurements from the head sensor were used to compute virtual camera position (viewpoint) to render more accurate views of the scene that support visual cues like looming and parallax. The second sensor, placed on the subject's hip, was used by the feedback-controlled treadmill interface. The hip position better reflects the user's center of mass and reduces the effects of turning or bobbing the head. To correct for spatial errors inherent in magnetic position trackers, distortion correction was applied to the readings of both sensors [Barabas et al. 2004b]. Speed commands were sent to the treadmill at 60 Hz. Treadmill speeds were recorded using a DataQ DI-151RS analog to digital converter (http://www.dataq.com/). To implement the feedback-controlled treadmill interface hardware and software, the changes described below were made.

2.1.1 *Hardware.* A Treadmill Interface Controller (TIC) was developed as an interface between the treadmill controller board and the VE workstation. The TIC applies a voltage to the analog speed input of the treadmill's motor driver board in response to serial port messages from the workstation. The TIC hardware is a purpose-built circuit employing an Atmel AT90S8515 microprocessor (http://www.atmel.com) and MAX201CPD RS-232 transceiver (http://www.maxim-ic.com).

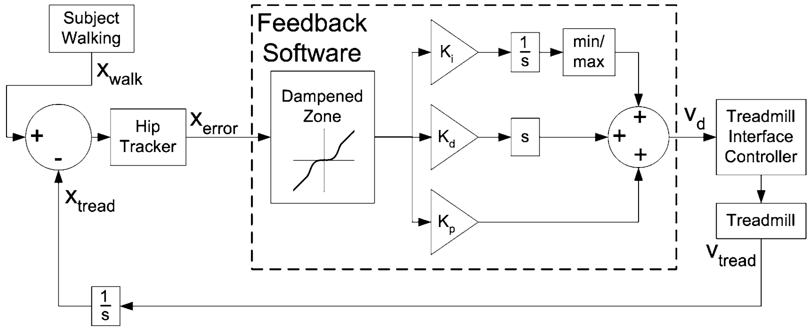

Fig. 1. Proportional-integral-derivative (PID) feedback loop for the treadmill. As the subject walks forward on the treadmill (x_{walk}), the distance of the hip tracker from x_0 (x_{error}) increases. The feedback software calculates a desired speed of the treadmill (v_d) that will minimize x_{error}. The calculation uses x_{error} itself, the change in x_{error} since the last frame, and the total cumulative x_{error}. Note that x_{error} can be negative, so the integral of x_{error} can become zero. The range of the integral term is restricted to prevent instability. The dampened zone ensures that there are no sudden starts or stops by reducing the effect of x_{error} as it approaches x_0. The resulting treadmill speed (v_{tread}) causes the subject to move back toward x_0, which will result in a reduction of x_{error}. This speed is then transformed into a voltage speed command for the TIC. The symbols s and $1/s$ represent the derivative and integral, respectively, as calculated in Eq. 1.

Since we do not need the entire range of possible treadmill speeds, the TIC was limited to a range of −0.45 V (0.675 mph (0.3 m/s) in reverse) to +4.55 V (6.825 mph (3.1 m/s) forward) from the reference voltage (0.45 V), using eight-bit pulse-width modulation for intermediate voltages. The software also imposes a further speed limit of 4 mph (see below) and does not allow the treadmill to go in reverse. If the software does not send a speed signal, the TIC will keep the treadmill at a constant speed.

The Woodway Desmo S is available with a serial interface for computer control, but can only accept commands at a maximum rate of 8/s. [Woodway 2004]. Bypassing this interface with our TIC allows the treadmill to respond to 31 commands per second. The Woodway motor driver board can accelerate the treadmill from 0 to 4 mph (1.79 m/s) in under 360 ms. Software safety measures were implemented to ensure that such dramatic acceleration commands are never sent to the treadmill.

2.1.2 *Software.* Desired treadmill speeds are sent to the TIC over the RS-232 serial port as single unsigned bytes, with a range of values from 0 to 254 (255 is reserved as an escape for emergency brake commands) and are converted to pulse-width modulated voltages the TIC sends to the treadmill.

The feedback-controller itself is a proportional-integral-derivative (PID) controller [Nise 2004] implemented in the VE application software (Figure 1). The VE application calculates the difference (x_{error}) between hip-tracker sensor position and intended position (x_0) (Figure 2). The desired speed is a function of the current x_{error}, of the time integral of x_{error}, and of the time derivative of x_{error}.

For every x_{error} reading at time t ($x_{\text{error}}(t)$), the feedback-controller sums three terms to calculate the desired speed at time t ($v_{\text{d}}(t)$), in inches/s.

$$v_{\text{d}}(t) = K_p x_{\text{error}}(t) + K_i \sum x_{\text{error}}(t) + K_{\text{d}}[x_{\text{error}}(t) - x_{\text{error}}(t-1)] \tag{1}$$

where $\sum x_{\text{error}}(t)$ is the sum of all $x_{\text{error}}(t)$ read so far and K_{p}, K_{i}, and K_{d} are the unitless coefficients for the proportional, integral, and derivative terms, respectively, which were derived through simulation and online testing. The integral or sum term eventually brings the subject close to x_0. As it continues to grow, the longer the subject is in front of x_0, the treadmill speed increases slowly to return the subject to x_0. Users that change speed frequently will spend more time away from x_0. Larger values of

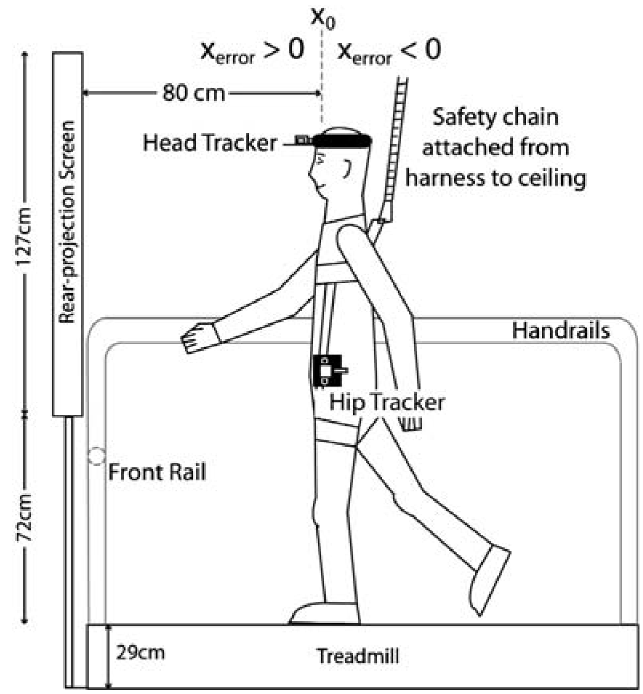

Fig. 2. Feedback-controlled treadmill setup. The speed of the treadmill is adjusted to keep the hip tracker at x_0. The distance from x_0, called x_{error}, is used by the feedback-controller to drive the speed of the treadmill. In addition to automated safety controls of the treadmill, subjects wear a safety harness and have side handrails that may be used to protect from a fall. The scene that they are viewing is rear-projected on a screen in front of the subject. Back and front ropes (not shown) are used to provide anchoring in the self-propelled condition.

K_p and K_d will cause the controller to return users to x_0 very quickly, but inexperienced users found the resulting sharp, sudden movements to be uncomfortable. To alleviate this, the feedback-controller was configured to allow overshoot, i.e., it initially allows users to go beyond x_0 during a change in speed.

Because subjects are allowed to overshoot the intended treadmill position when accelerating, x_0 must be chosen to provide sufficient physical space for the overshoot. There must be a sufficient safety margin behind the subject to decelerate the treadmill belt to a stop without risking the subject falling off the back of the treadmill.

The software was designed not to allow reverse movement, since pilot subjects said that it felt disconcerting. Therefore, sudden halts by the subject will result in them coming to rest behind x_0. It was anticipated that subjects would correct their position by proceeding to walk again.

In addition, a dampened zone was added prior to the PID portion of the controller to prevent sudden stops or starts at very small magnitudes in x_{error}, which is especially important if a subject sways forward or backward while standing still. Note that in our implementation of the dampened zone, the values of x_{error} are reduced, not set to zero as in a true dead zone. The amount of reduction is a function of the actual x_{error}. When x_{error} is zero, the output of the dampened zone is zero and there is no reduction when the magnitude of x_{error} is greater than 10 cm. Intermediate values of x_{error} are multiplied by a smooth, monotonic curve that ranges from 1 to 0.

Before sending a speed command to the treadmill, the feedback-control software makes several safety checks:

1. The user must be within a specified 3D safety zone indicating that the user is not going to step off the side or back of the treadmill. The safety zone is set tighter behind the subject.
2. If the subject's hip position drops lower than 44 cm from the plane of the treadmill, the software triggers an emergency brake, assuming that the hip-mounted sensor, with or without the user, has fallen.
3. If the hip position moves faster than 5.1 mph (2.3 m/s) for more than 300 ms the software will trigger an emergency brake. This protects against stumbles and falls.
4. The software is set to prevent the treadmill from exceeding a specified maximum speed, which is currently 4.0 mph (1.79 m/s).
5. As a result of the latter speed limit, if the subject is maintaining the maximum treadmill speed, the feedback-controller is unable to lower the positive error term, since the treadmill cannot go any faster. The integral of the error will continue to rise without limit. When this happens, the treadmill might stay at maximum speed even when the subject slows down or stops, since the integral term will not reduce to a reasonable value in time. This is a potentially dangerous situation, since it increases the likelihood that a subject will go off the back of the treadmill. Therefore, the PID software has a maximum integral term limit to protect against this error.
6. The software triggers an emergency brake if commanded by the experimenter.

2.2 Evaluation Study

To ensure the safety of the feedback-controlled treadmill under extreme conditions, subjects performed faster accelerations and decelerations than expected to occur in our future experiments on the treadmill (*abrupt change* condition). To demonstrate reasonable operation when the subject was making more natural accelerations and decelerations, we evaluated sinusoidal variations in speed (*continuous change* condition). As matching walking speed with perceived motion may not be veridical, subjects walked with and without guidance from a moving object (*object following* and *scene matching* conditions, respectively). These four conditions were conducted as a randomized 2 × 2, within-subject, experimental design with all four conditions blocked for each treadmill mode (self-propelled and feedback controlled).

2.2.1 *Subjects.* The study was reviewed and approved by our Internal Review Board and conformed to the tenets of the Declaration of Helsinki. Subjects gave written, informed consent before participating. Six subjects (4 female) with normal, or corrected-to-normal, visual acuity participated in the study. Their ages ranged from 21 to 60 years old (37 ± 14.2). All subjects were naive about the operation of the feedback-controlled treadmill and had no previous experience with it. Four subjects had previously participated in experiments in our virtual environment and three of those had used the treadmill in its self-propelled mode. Each subject in the experiment walked about a total of 2.5 ± 0.2 miles (4.0 ± 0.3 km).

2.2.2 *Experiment Design.* Each subject performed the following tasks (described in detail below): (1) Preferred walking speed in 15 m open corridor; (2) comfortable real-world walk; 3) comfortable walking in first treadmill mode; (4–7) speed-matching tasks for first treadmill mode in random order; (8) questionnaire for first treadmill mode; (9) comfortable walking in second treadmill mode; (10–13) speed-matching tasks for second treadmill mode in random order; and (14) questionnaire for second treadmill mode.

Preferred walking speed in the real world was measured by having the subject walk down a straight unobstructed corridor, at the Schepens Eye Research Institute (SERI), for a distance of 15 m, while being timed [Soong et al. 2004]. Acceleration and deceleration times during the first and last 3 m were not included in the measurement. The test was repeated three times and the results averaged.

In the *comfortable real-world walk*, subjects were told to walk at their "comfortable, normal walking speed" for 5 min in the corridors of SERI. Pulse rate was measured right before and right after the walk using an Opto-Electronics PU-711 Pulse Monitor. A rest period was given after that walk until heart rate returned to the at-rest value.

Before beginning the treadmill tasks, subjects were given a brief tutorial on how to walk on the treadmill for each treadmill mode. During the self-propelled tutorial, the subject, chose a preferred angle of incline. The incline reduces the amount of necessary force to push against the friction of the treadmill. The median angle of incline was 8° (range 4.5°–11°).

The subjects were presented with a virtual shopping mall corridor (the infinite corridor). Sidewalls had photographs of storefronts that repeated every 150 m and both the ceiling and floor were textured. The floor was textured with floor tiles, each 0.67×0.61 m in size.

For each treadmill mode, the experiment was broken into five tasks that were performed separately. The feedback-controlled tasks were done on a different day than the self-propelled tasks, with the exception of one subject who took a 1-hr break between the two series of tasks. In all tasks, the simulated direction of subject movement was straight down the corridor.

The starting task for a given mode was always the *comfortable walking task*, where subjects were told to walk at their "comfortable, normal walking speed" down the simulated corridor for 5 min. They were told not to consciously try to maintain a given speed, but also not to consciously change their walking speed. The display simulated progression down the infinite corridor, at the speed of treadmill movement. Pulse rates were recorded both before and after the walk. The walking speed during the comfortable walking task was averaged, excluding the first and last minute intervals.

The four *speed-matching tasks* included two factors (*speed change* and *speed cue*) each with two conditions. The speed-cue conditions were object following and scene matching, and the speed-change conditions were abrupt and continuously changing. The four tasks were presented in a random order for each subject.

2.2.2.1 *Speed-cue conditions.* In the object-following condition, subjects matched their walking speeds to that of a moving, wheeled trashcan. The trashcan trajectory was parallel to the subjects' direction of locomotion, but offset by 10 cm to the right of the subject. Subjects were told to keep the trashcan at a fixed distance in front of them. The distance to the trashcan was not specified, but they were asked to be consistent and a distance of about 5 to 7 of the infinite corridor's floor tiles was suggested. We expected that subjects would be able to match the speed of the trashcan quite well in either treadmill mode, since subjects could simply keep the size of the trashcan constant on the screen.

In the scene-matching condition, the scene represented travel down an empty corridor at a speed that was set by the computer, independent of the treadmill movement. Subjects were told to walk on the treadmill at a speed that would make the scene movement feel "correct." We expected that subjects would move slower than the actual scene speed, since previous studies [Harris et al. 2000; Loomis and Knapp 2003] have shown a perceived compression of depth in a VE, which would result in a perceived decrease in velocity of the scene. Note that in the scene-matching condition, no trashcan was present in the corridor.

2.2.2.2 *Speed-change conditions.* In the abrupt-change condition, the speed of the trashcan or scene (*input speed*) was constant for 30 s, and then would abruptly change. The appearance of a small yellow circle in the upper right of the display would precede the change by 5 s. The diameter of the yellow circle was 10 inches, spanning about 13° and was positioned so that it could not occlude the trashcan.

For each 30 s segment, the input speed was 0.5, 1, 1.5, 2.0, 2.5, 3.0, or 3.5 mph (0.22, 0.45, 0.67, 0.89, 1.12, 1.34, and 1.56 m/s, respectively). The abrupt-change tasks lasted 14.5 min each.

The abrupt changes induced subjects to dramatically change their walking speed outside the range that would be normally used. Speed changes of positive and negative 0.5, 1, 1.5, 2.0, 2.5, 3.0, and 3.5 mph were included (0.22, 0.45, 0.67, 0.89, 1.12, 1.34, and 1.56 m/s, respectively).

In the continuous-change condition, the input speed was composed from a summation of three sinusoids at different frequencies and amplitudes:

$$v(t) = 2 + \left(\sum_{i=1}^{3} A_i \sin(2\pi \omega_i t)/3 \right) \tag{2}$$

where $v(t)$ is the speed of the viewpoint or lead object at time t, ω_i were the frequencies 0.033, 0.083, and 0.117, Hz and A_i were the amplitudes 2.411, 0.959, and 0.68, respectively. The amplitudes were selected to ensure that the maximum acceleration and deceleration was 0.5 mph/s (0.22 m/s^2). The sinusoids were added to 2 mph (0.89 m/s), which made the range of speeds vary between 0.7 mph (0.31 m/s) and 3.2 mph (1.43 m/s). The same sinusoid sum was used for all subjects in all of their continuous-change tasks. The sum of three sinusoids is used to prevent a subject from predicting movement [Rizzo et al. 2005]. The continuous-change tasks were each 10 min long.

The abrupt change condition allows analysis of safety under conditions of extreme usage, subject control of their walking speed, and the ability of each treadmill mode to constrain subject position on the treadmill, both within and across subjects. The continuous-change condition allows analysis of subject control (by understanding how well they matched oscillating speed changes), demonstrates safety of the system when being used in a more likely scenario, and allows analysis of position constraint when many speed changes are present.

2.2.2.3 *Questionnaire.* After a subject completed all of the tasks for each of the two treadmill modes, the subject was asked to rank (-3 through 3), on a paper questionnaire, the ease of speeding up, slowing down, maintaining speed, level of physical exertion, and overall comfort compared to walking normally. Separate questions were asked in order to analyze speed changes from a stopped position and from a nonzero speed. A rating of zero indicated that the mode of locomotion was comparable to walking normally for that question. A negative value indicated that the mode of locomotion was more difficult than walking normally. The subjects answered the questionnaire without being able to compare their responses for the other mode of locomotion.

2.3 Statistical Analysis

There were only a few places where a normal distribution could be assumed. Therefore, differences between real-world walking, feedback-controlled treadmill, and self-propelled treadmill were analyzed using the Wilcoxon Signed Rank Test (using signrank in Matlab), unless otherwise specified in Section 3. Differences are reported as statistically significant at the 95% confidence level ($p < 0.05$).

3. RESULTS

The brief training was sufficient for the subjects to complete the tasks on both treadmill modes with no safety incidents.

3.1 Overall Positioning of the Subject on the Treadmill

The purpose of the feedback system was to keep the user near the intended treadmill position, x_0. Figure 3 shows the positions of all subjects during all of the feedback-controlled trials. More than 84.0% of the samples were within (arbitrarily selected) 15 cm. As described in Section 2, the feedback-controller

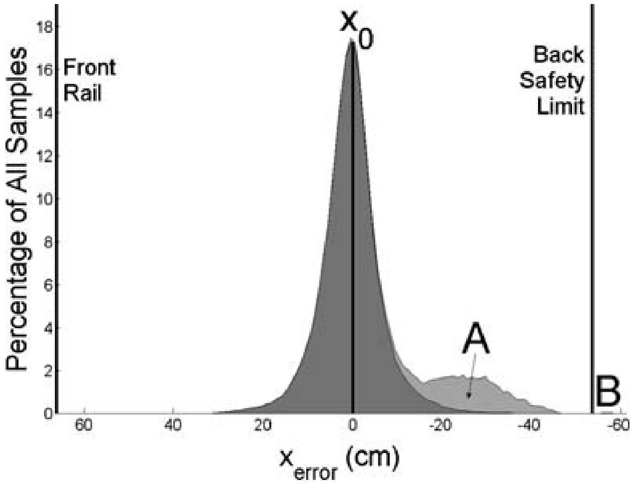

Fig. 3. Location of all subjects during all tasks with the feedback-controlled treadmill. The complete set of 1,173,137 samples are shown with a bin size of 1 cm. Region A (lighter shade) marks locations behind x_0 where subjects came to rest after abrupt halts. The darker shade marks the remaining 999,939 samples. Any samples that fell behind the back safety limit (53 cm) would have triggered an emergency brake. Region B (0.05% of the samples) marks where one subject turned to the left 90°, after stopping on the treadmill.

software permitted backward overshoot when the user stopped and did not enable the treadmill to drive in reverse. Thus, a user that stopped walking came to rest behind x_0. The samples collected from subjects at rest behind x_0 are shown in a lighter shade (region A) in Figure 3. At-rest samples (region A) were identified for each abrupt speed change task by calculating the time delay (lag) of the treadmill speed relative to the input speed using cross-correlation [Knapp and Carter 1976].[1] This yielded one time delay, per subject, for the whole task. At-rest samples were defined as the position samples where the input speed was zero after being shifted by the time delay. Note that errant stops made by subjects, such as when they mistakenly thought that the object had stopped when it had actually just slowed, were not included in region A. With the at-rest data removed, 95.5% of the remaining samples were within 15 cm of x_0. The average position for each subject was always less than 1 cm from x_0.

The self-propelled treadmill mode kept subjects in a smaller area than the feedback-controlled treadmill, because of the back rope holding the subject in a fixed position whenever they moved forward. With at-rest samples dropped, 97.7% of samples were within 15 cm of the subjects' average positions and 2.4% were between 15 and 50 cm behind (away from the screen) the average positions. There were no samples outside of these ranges. The average position for the self-propelled mode was $+15$ cm from x_0 and ranged from $+5$ to $+26$ cm as a result of the tethers and treadmill inclines used in the self-propelled mode.

3.2 Positioning of the Subject by Task

The distributions of position error for each task and each subject were examined. Position range varied between tasks, but it was much less when subjects maintained a constant speed (during the comfortable walking task) than during the speed-matching tasks. Although individual task position distributions appeared approximately Gaussian, none were (Lilliefors Test, $p < 0.01$, $n > 6000$ for preferred walking tasks and $n > 16{,}200$ for the speed-matching tasks). Therefore, we report the range between the 99th

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[1] This technique to calculate the time delay was also used for calculating the time delay in the sinusoidal tasks (see below).

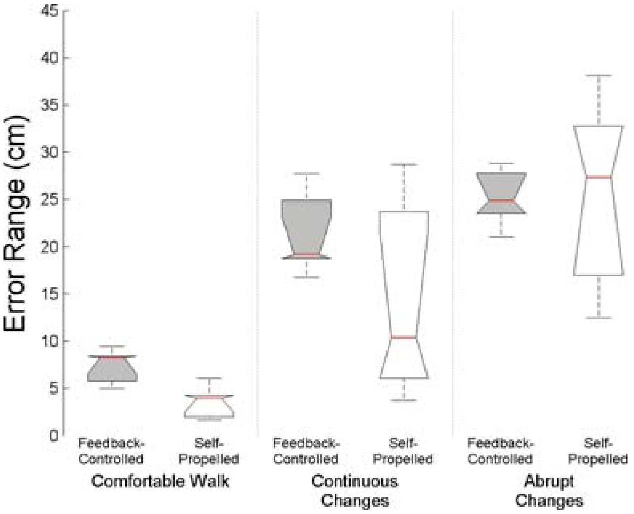

Fig. 4. Distribution of 99th percentile ranges of position (error range) across all subjects for the feedback-controlled (shaded) and self-propelled (open) treadmill modes during comfortable walk and object-following tasks. The median of the error ranges was smaller when walking at a constant speed (comfortable walk task) than when the user was performing accelerations and decelerations. Comparing the self-propelled to the feedback-controlled mode, the median error range was smaller in the constant speed ($W_5 = 1$, $p = 0.063$), not significantly smaller in the continuous-change condition ($W_5 = 3$, $p = 0.150$), and not different in the abrupt-change condition ($W_5 = 10$, $p = 1.0$).

percentiles of the position range (a 99% confidence interval) as the *error range* of each subject. These are shown in Figure 4.

To illustrate that a large proportion of the error range is because of lags and leads in acceleration, we also calculated the 90th percentile error range. With this definition, error ranges, while doing the comfortable walk task, were less than 6 cm for the feedback-controlled mode and less than 5 cm for the self-propelled mode. For the speed-change conditions, the error range was less than 15 cm with the feedback-controlled mode and less than 7 cm with self-propelled (with one exception, whose ranges were 9 and 22 cm for self-propelled continuous and abrupt changes, respectively).[2] All medians were lower for self-propelled than feedback-controlled walking.

3.3 Comfortable Walking Speed in Treadmill Modes

Compared to real-world walking (average 1.25 m/s), the comfortable walking speed with feedback-controlled mode was not significantly slower (average 1.2 m/s; $W_5 = 5$, $p = 0.313$), while with self-propelled mode it was significantly slower (average 0.9 m/s; $W_5 = 0$, $p = 0.031$). In the feedback-controlled mode, two subjects walked faster than their real-world walking speed. For the self-propelled mode, all subjects were slower than their real-world preferred walking speed. Subjects had a slower comfortable walking speed on the self-propelled than on the feedback-controlled mode, but this difference only approached significance (average difference: 0.3 m/s; $W_5 = 1$, $p = 0.063$).

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[2] One subject, in the self-propelled mode, had a 90th percentile larger than 7 cm in both abrupt (22 cm) and continuous-changes (9 cm) conditions. Both values were outliers, which were defined as values larger than 1.5 times the size of the interquartile range (75th percentile minus the 25th percentile) added to the 75th percentile value [Moore and McCabe 1999]. The next highest values were 7 and 4 cm in the abrupt and continuous-change categories, respectively. This subject had the highest incline setting (11°). These large values of the 90th percentile subject positions in the abrupt and continuous-change conditions were as a result of the subject coming to or from a stop on a steep incline when the object was still moving.

3.4 Physical Exertion in Each Mode of Locomotion

The difference in pulse rates between measurements taken before and after the preferred walking speed task was used as the measure of physical exertion. There was no significant pulse rate difference when comparing real-world walking (average difference of 16 beats/min) with feedback-controlled mode (average difference of 10 beats/min, $W_5 = 8$, $p = 0.690$), but there was a significant effect when compared to self-propelled mode (average difference of 41 beats/min, $W_5 = 0$, $p = 0.031$). The difference in pulse rates was greater with self-propelled than feedback-controlled mode ($W_5 = 0$, $p = 0.031$). In the questionnaires, all subjects answered that there was more physical exertion necessary with the self-propelled mode (average score: 1.92; $W_5 = 0$, $p = 0.031$) and with the feedback-controlled (average score: 0.42; $W_5 = 0$, $p = 0.063$) than while walking normally (corresponds to a score of zero). In the comments section of the questionnaire, the large amount of physical exertion was a common complaint among subjects about the self-propelled mode of locomotion.

3.5 Subjects' Ability to Control Treadmill in Each Mode of Locomotion

We examined only the object-following tasks and excluded the moving-scene tasks, because subjects were better at detecting a change in object speed than they were in detecting a change in scene speed. The difference between the object-following and scene-matching tasks is examined later.

3.5.1 *Response Time of Subjects to Abrupt Speed Changes.* The response time is a measure of the ability of the system, including the subject, to match abrupt speed changes. Response time was defined as the time shift of the treadmill speed that best approximated the abrupt speed change. As illustrated in Figure 5, in the interval 15 s on either side of the abrupt-speed change, gain and scale adjustments were used to first equate object and treadmill average speeds, then a time shift was calculated that provided a best fit of the treadmill speed to the object speed (in the mean squared error sense). To avoid limitations in the response time because of the subject's ability to detect a small speed change, only speed changes higher than 0.5 mph (0.22 m/s) were included. For abrupt speed changes, subjects took 0.1 s longer to slow down or stop with feedback-controlled than self-propelled mode (average response time of 1.7 versus 1.6 s, Wilcoxon rank test $Z_{69} = 2.54$, $p = 0.011$). When accelerating, subjects took 0.5 s longer with feedback-controlled than self-propelled mode (average response time of 2.6 versus 2.1 s, Wilcoxon rank test $Z_{63} = 2.97$, $p = 0.003$).

3.5.2 *Subjects' Ability to Match Continuously Changing Speed.* In analyzing the walking speeds at the three frequencies, we did not assume that the treadmill and subject's response to an input speed was linear, since the treadmill has a maximum acceleration, speed, and a damped zone. Since subjects are better at detecting small changes in the object than scene speed, we did not use the moving-scene task data here. We calculated a gain for each frequency in the compound waveform discussed in Section 2. The gain for a subject task was calculated as follows:

$$Gain = |F(v_t(t))|/|F(v_o(t))| \qquad (3)$$

where $v_t(t)$ was the speed of the treadmill at time t, $v_o(t)$ was the speed of the object at time t, and $|F|$ was the amplitude of the Fourier Transform. For both modes, subjects performed comparably in the two higher frequencies (0.083 and 0.117 Hz). The differences in gain between self-propelled (average gains: 0.74 and 0.74) and feedback-controlled (average gains: 0.85 and 0.66) were not significant ($W_5 = 5$, $p = 0.313$ and $W_5 = 6$, $p = 0.438$, respectively). For the lower frequency (0.033 Hz), the difference in gain (average self-propelled: 0.83, feedback-controlled: 1.00) was statistically significant ($W_5 = 0$, $p = 0.031$). Average gains for all three frequencies, in both treadmill modes, were above noise (Wilcoxon Rank Sum Test $n = 6$, $p < 0.001$).

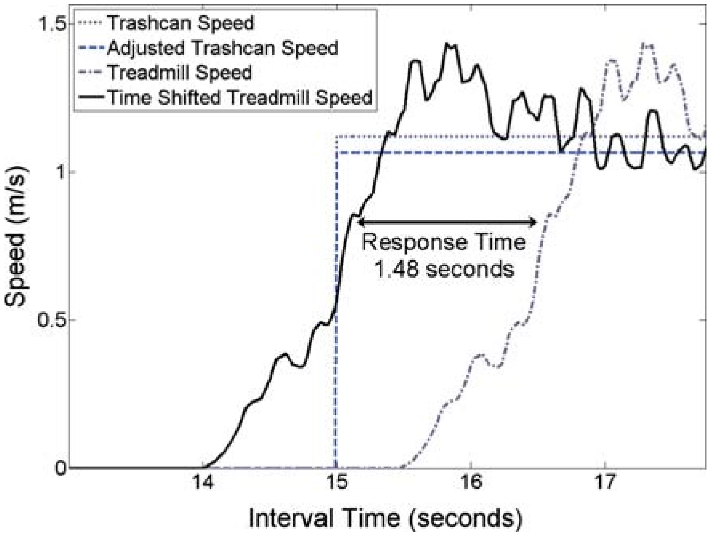

Fig. 5. Illustration of response time calculation. The entire interval used for these calculations was 30 s long (15 s before the input step and 15 s after); only a 5 s segment is shown here so that the response time is evident. Before calculating the response time, the trashcan speed was adjusted to match the average treadmill speed of each 15 s interval. The time delay of the treadmill speed is the shift that best approximates the adjusted trashcan speed. This time delay is the response time. The adjustment of trashcan speed for this fitting procedure was necessary, because subjects occasionally underestimated the magnitude of change in the object speed, which caused the mean squared error fitting to produce erroneous results.

3.5.3 *Subjects' Ability to Match Abruptly Changing Speed.* To assess performance of the abruptly changing speed task, the difference in the standard deviation of the subject to trashcan distance was analyzed. A large standard deviation implies that a subject did not match the trashcan speed well. There was no significant difference in standard deviation between the self-propelled (average standard deviation: 2.4 m) and the feedback-controlled (average standard deviation: 2.4 m) modes for the abruptly changing speeds condition ($W_5 = 8$, $p = 0.688$).

3.5.4 *Questionnaire Responses.* There was no difference in the subjects' questionnaire responses between the feedback-controlled and the self-propelled treadmill modes ($p > 0.625$), except for physical exertion (discussed above) and the ability of subjects to shift from one constant speed to another. In the latter, subjects tended to score the feedback-controlled mode higher than the self-propelled mode (average scores: -0.33 and -1.17, respectively), but the difference was not significant ($W_5 = 2$, $p = 0.250$). Most complaints about the feedback-controlled treadmill involved accelerating from a stopped position. Subjects felt that the treadmill accelerated too quickly with their first step. However, subjects still scored their ability to accelerate from a stop on the feedback-controlled and self-propelled modes with nearly the same values (average scores: -1.42 and -1.33, respectively; $W_5 = 2.5$, $p = 1.0$). No response by any subject rated the treadmill modes better than walking normally. For the average of responses to all questions, there was a small, but not significant, difference between the two treadmill modes in favor of the feedback-controlled mode (self-propelled: -1.02, feedback-controlled: -0.71; $W_5 = 2.5$, $p = 0.250$).

3.6 Scene Speed Estimation

One limitation of most VEs is their inability to make locomotion feel natural to the user. This may have adverse effects on a subject's ability to track their own position and, thus, affect their responses. Durgin

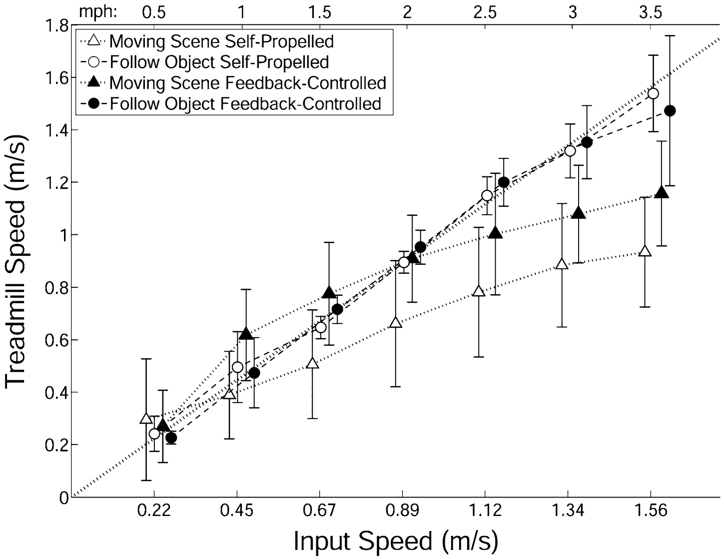

Fig. 6. Treadmill speeds for the abrupt speed-change tasks. If subjects adopted a walking speed that matched the task, the data would fall along the 1:1 diagonal (dotted line). Subjects tended to underestimate the scene speed at higher speeds. The difference between scene and treadmill speeds was larger for subjects using self-propelled locomotion at higher speeds. Error bars are standard deviation. Data points are grouped by speed and shifted slightly from actual value to show error bars cleanly.

et al. [2005a] found that speed estimation of egocentric movement varied according to the amount of self-movement by a subject.

Figure 6 shows the average speeds, across all subjects, of the four speed-matching tasks during the abrupt speed-change condition. The average was taken over the time interval starting 10 s after an abrupt object speed change and ending 5 s before the next speed change (after being shifted by the average time delay for the task). As expected, subjects performed better at the object-following tasks (circles) than when trying to match the moving scene (triangles), with the moving scene being underestimated by a larger margin as speed increased. This difference between the object-following and moving-scene tasks became significant at speeds higher than 0.45 m/s for the self-propelled mode ($p < 0.007$) and higher than 0.89 m/s for the feedback-controlled mode ($p < 0.031$). There was a statistically significant difference in the moving scene task between self-propelled and feedback-controlled at speeds greater than 0.22 m/s ($p < 0.047$). The difference was a nearly constant shift that averaged 0.23 m/s, with a range of 0.20 to 0.27 m/s.

In the continuous-changing speed tasks, subjects were better able to match the oscillations when following the object than when attempting to match the moving scene in both modes of locomotion at all three frequencies ($W_5 = 1$, $p = 0.031$). There were no significant differences between the self-propelled and feedback-controlled modes in the moving scene task with continuous speed changes (frequency 0.033 Hz: $W_5 = 9$, $p = 0.844$; 0.083 Hz: $W_5 = 7$, $p = 0.563$; 0.117 Hz: $W_5 = 1$, $p = 0.063$).

4. DISCUSSION

Our PID feedback-controlled treadmill locomotion interface was found to be safe, required minimal training for use, allowed easy, voluntary changes in walking speed, required no more physical exertion than natural walking, and maintained the user at an adequately consistent distance from the display screen even with considerable changes in walking speed. In addition, subjects were found to estimate the speed of the moving scene more accurately in the feedback-controlled mode.

4.1 General Requirements

4.1.1 *Subject Positioning.* With our feedback-controlled locomotion interface, variation in position on the treadmill, even under extreme changes of speed, was sufficiently small to maintain user safety (Figure 3). In addition to safety, a fairly consistent visual extent of the display screen is important in various experimental paradigms. This was possible for all conditions and especially when the subject walked at a constant speed (Figure 4). During all the studies reported here, the visual angle spanned by the screen, varied infrequently (1% of the time) by more than about 19% and, while walking at constant speeds, all subjects were kept within 9 cm of x_0, 99% of the time, which corresponds to a change in visual extent of 7% or less.

Generally, there was a smaller variation of visual extent on the self-propelled mode than feedback-controlled, since the ropes used in the self-propelled mode of locomotion kept subjects in a smaller area. A further analysis of the visual extents in the two treadmill modes appears in Lichtenstein et al. [2006].

4.1.2 *Physical Exertion.* Murray et al. [1985] found a pulse rate difference between real-world walking and treadmill walking, but only when the treadmill was going faster than the subject's comfortable walking speed (their "free walking" condition). Murray et al. [1985] did not find a statistically significant difference at the subject's comfortable walking speed. Similarly, our questionnaire and pulse rate results did not suggest that the feedback-controlled treadmill requires more exertion than normal walking at the subject's preferred walking speed. However, on average, subjects had a slower preferred walking speed on the feedback-controlled treadmill than when walking normally, which could imply that subjects going at comparable speeds would have a lower pulse rate when walking normally.

We anticipate being able to acquire more data in a walking experiment using the feedback-controlled treadmill, since subjects will be able to participate for a longer period of time before becoming fatigued. The lower preferred walking speeds of subjects using the self-propelled mode may have been as a result of the high amount of physical exertion required; subjects may have lowered their speed to compensate for this higher physical exertion required.

4.1.3 *Subjects' Ability to Control Walking on the Feedback-Controlled Treadmill.* Subjects were able to walk on the feedback-controlled treadmill after no more than a brief training session. Subject apprehension about general treadmill walking has been suggested in Murray et al. [1985]. Our subjects may have been especially apprehensive on the feedback-controlled treadmill, since the treadmill was not always moving at a constant speed, especially when subjects began walking. Some subjects thought the treadmill responded too quickly to their first step when accelerating from a stop, so it was suggested that they accelerate from stop with a half step. This would have increased the response times for acceleration on the feedback controlled treadmill, which was observed. Future work will have to include modifying the feedback controller to provide a more comfortable first step. This is especially important for walkers who have an extremely slow cadence, such as the elderly, since the treadmill could come to a stop between steps.

The continuously changing speed object-following task indicates that subjects had slightly more control over speed changes using the feedback-controlled mode, since they could better match the low-frequency component of the changing trashcan speed. However, subjects performed comparably on either treadmill mode when the speed matching did not require frequent changes, as in the abrupt-change task.

4.2 General Issues

The self-propelled mode does not duplicate natural walking, since it requires significant changes to the gait because of the back rope and the treadmill incline. These factors alter the perception of walking, but are not necessary in the feedback-controlled mode. Although subjects generally preferred the feedback-controlled treadmill to the self-propelled, none said that the feedback-controlled mode accurately simulated natural walking. This can be attributed to several differences between walking on solid ground and on a feedback-controlled treadmill. The first difference is the movement of the treadmill belt underneath the foot. This serves to reduce the ground reaction force on the foot of the subject during a step that can result in a feeling of slipping rather than walking. The feedback-controlled treadmill partially mitigates this by letting the subject physically move forward.

Because of the relatively short length of the treadmill, the maximum treadmill speed, and desire to maintain comfort and safety by limiting acceleration, some subjects reach the front end of the treadmill when beginning a walk, which causes them to prolong the initial ramp-up of walking speed and increases the average response time to abrupt speed changes. A subject walking off the front of the treadmill is not likely, since subjects can see the front screen and will adjust their speed accordingly. However, this increases the number of steps in an initial walking acceleration, which will reduce the "natural" walking feeling and could have led to systematic errors in some of our measurements. Moving the subject backward on the treadmill could help with that initial acceleration, but increased the risk of falling off the back of the treadmill. Asymmetric acceleration limits may also improve this.

4.3 Scene Speed Underestimation

It is interesting to note the relations between our results and those of previous studies. The scene-matching task results show that subjects mostly underestimated the speed of the moving scene, regardless of mode. According to Banton et al. [2005], the underestimation is as a result of inadequate laminar flow, which may account for some of our results. However, Durgin et al. [2005a] found that these visual field speed judgments do not just depend on visual input, but also on self-motion of the subject, e.g., whether the subject was walking on a treadmill.

Other studies [Loomis and Knapp 2003; Willemsen and Gooch 2002; Witmer and Kline 1998] have found that there was a general compression of depth inside VEs. This would make subjects feel that the moving scene was going slower than its actual speed while leaving performance in the object following task unaffected (as we found). Thurrell et al. [1998] found that optic flow speed is overestimated at low speed and underestimated at higher speeds while subjects walked on a treadmill in self-propelled mode. This is similar to the moving-scene task results we observed (Figure 6). Thurrell et al. [1998] also found that subjects were most accurate when they could walk at their preferred walking speed (called "normal" in their study). This effect was not observed here, since the average preferred walking speed was 0.9 m/s on the self-propelled mode, which was not the speed where subjects were most accurate (0.45 m/s). Nor was the effect observed for the feedback-controlled mode where subjects averaged a 1.2 m/s preferred walking speed and were most accurate at 0.9 m/s.

At speeds of 0.45 m/s and greater, subjects were better able to match the speed of the scene when using the feedback-controlled than when using the self-propelled treadmill. This makes the feedback-controlled mode a more attractive choice for experiments where the subject's accuracy is important.

The average walking speed on the feedback-controlled mode was 0.22 m/s higher than the speed while on the self-propelled mode for all moving scene speeds from 0.45 m/s and faster. At first glance, physical exertion might seem a likely cause of the shift, but Bakdash et al. [2005] found that encumbered subjects did not change optic flow speed estimates. In addition, if physical exertion was limiting the subjects greatly, the object-following results should indicate a difference between modes, but that was not found. Furthermore, Proffitt et al. [2003] found that subjects made greater estimates of depth when burdened, which further indicates that the difference between the self-propelled and feedback-controlled modes in the matching-scene tasks is not because of physical exertion.

ACKNOWLEDGMENTS

Supported in part by NIH grant #EY12890. We thank Richard Price of the Physics Department, University of Texas at Brownsville, for useful comments on drafts of this manuscript. We thank Aaron J. Mandel of SERI for his help gathering treadmill calibration data.

REFERENCES

Apfelbaum, H., Pelah, A., and Peli, E. 2007. Heading assessment by "tunnel vision" patients and control subjects standing or walking in a virtual reality environment. *ACM Transactions on Applied Perception 4*, 1, Article 8, 1–16.

Bakdash, J. Z., Augustyn, J. S., and Proffitt, D. R. 2005. Effects of effort and reduced visual cue information on perceived walking speed (abstract). *Journal of Vision* 5, 8, 747a.

Banton, T., Stefanucci, J., Durgin, F. H., Fass, A. M., and Profitt, D. 2005. The perception of walking speed in virtual environments. *Presence 14*, 4, 394–406.

Barabas, J., Woods, R. L., Goldstein, R. B., and Peli, E. 2004a. Perception of collisions while walking in a virtual environment with simulated peripheral vision loss (abstract). *Journal of Vision 4*, 8, 806a.

Barabas, J., Goldstein, R., Apfelbaum, H., Woods, R. L., Giorgi, R., and Peli, E. 2004b. Tracking the line of primary gaze in a walking simulator: modeling and calibration. *Behavior Research Methods, Instruments, & Computers 36*, 4, 757–770.

Bardy, B. G., Warren, W. H., Jr., and Kay, B. A. 1999. The role of central and peripheral vision in postural control during walking. *Percept. Psychophy 61*, 7, 1356–1368.

Chaudhury, S., Eisinger, J. M., Hao, L., Hicks, J., Chivukula, R., and Turano, K. A. 2004. Visual illusion in virtual world alters women's target-directed walking. *Expe. Brain Res. 159*, 360–369.

Cutting, J. E., Vishton, P. M., and Braren, P. A. 1995. How we avoid collisions with stationary and moving obstacles. *Psychol. Rev. 102*, 4, 627–651.

Cutting, J. E., Readinger, W. O., and Wang, R. F. 2002. Walking, looking to the side, and taking curved paths. *Percept Psychophys 64*, 3, 415–425.

Darken, R. P., Cockayne, W. R., and Carmein, D. 1997. The Omni-Directional Treadmill: a locomotion device for virtual worlds. in *User Interface Software and Technology '97*, Banff, Canada. 213–221.

Distler, H. K., Pelah, A., Bell, A. G., and Thurrell, A. E. I. 1998. The perception of absolute speed during self-motion (abstract). *Perception 27s*, 139.

Durgin, F. H., Gigone, K., and Scott, R. 2005a. Perception of visual speed while moving. *J. Exp. Psychol. Hum Percept. Perform. 31*, 339–353.

Durgin, F. H., Pelah, A., Fox, L. F., Lewis, J., Kane, R., and Walley, K. A. 2005b. Self-motion perception during locomotor recalibration: More than meets the eye. *J. Exp. Psychol. Hum Percept. Perform. 31*, 398–419.

Fajen, B. R. and Warren, W. H. 2003. Behavioral dynamics of steering, obstacle avoidance, and route selection. *J. Exp. Psychol. Hum. Percept. Perform. 29*, 2, 343–362.

Fajen, B. R. and Warren, W. H. 2004. Visual guidance of intercepting a moving target on foot. *Perception 33*, 689–715.

Foo, P., Warren, W. H., Duchon, A., and Tarr, M. J. 2005. Do humans integrate routes into a cognitive map? Map-versus landmark-based navigation of novel shortcuts. *J. Exp. Psychol. Hum. Percept. Perform. 31*, 2, 195–215.

Gottlieb, D. D., Freeman, P., and Williams, M. 1992. Clinical research and statistical analysis of a visual field awareness system. *J. Am. Optom. Assoc. 63*, 8, 581–588.

Harris, L. R., Jenkin, M., and Zikovitz, D. C. 2000. Visual and non-visual cues in the perception of linear self motion. *Exp. Brain. Res. 2000*, 135, 12–21.

Hollerbach, J. M., Xu, Y., Christensen, R., and Jacobsen, S. C. 2000. Design specifications for the second generation Sarcos Treadport locomotion interface. In *Haptics Symposium, Proc ASME Dynamic Systems and Control Division*, Orlando, DSC-Vol. 69–72, 1293–1298.

Iwata, H. 1999a. Locomotion interface for virtual environments. In *Robotics Research: The 9th International Symposium*, Snowbird, UT, Springer-Verlag, New York. 220–226.

IWATA, H. 1999b. Walking about virtual environments on an infinite floor. In *Proceedings IEEE Virtual Reality '99*, Houston, TX. 286–293.

KNAPP, C. H. AND CARTER, G. C. 1976. The generalized correlation method for estimation of time delay. *IEEE Transactions on Acoustics, Speech and Signal Processing 24*, 4, 320–327.

LI, L. AND WARREN, W. H. 2000. Perception of heading during rotation: sufficiency of dense motion parallax and reference objects. *Vision Research 40*, 28, 3873–3894.

LICHTENSTEIN, L., BARABAS, J., WOODS, R. L., AND PELI, E. 2006. Maintaining position and display perspective in a walking simulator while self-pacing on a treadmill. In *SID International Symposium*, San Francisco, CA. vol. 37. 295–298.

LOOMIS, J. M. 1992. Presence and distal attribution: phenomenology, determinants, and assessment. In *Human Vision, Visual Processing, and Digital Display III / Human Perception, Performance, and Presence in Virtual Environments*, San Jose, CA, The International Society for Optical Engineering (SPIE), 1666. 590–595.

LOOMIS, J. M. AND KNAPP, J. M. 2003. Visual perception of egocentric distance in real and virtual environments. In *Virtual and Adaptive Environments*, J. Hettinger, and M. W. Haas, Eds. Erlbaum, Hillsdale, NJ. 21–46.

LOOMIS, J. M., DA SILVA, J. A., FUJITA, N., AND FUKUSIMA, S. S. 1992. Visual space perception and visually directed action. *J. Exp. Psychol. Hum. Percept. Perform. 18*, 4, 906–921.

MINETTI, A. E., BOLDRINI, L., BRUSAMOLIN, L., ZAMPARO, P., AND MCKEE, T. 2003. A feedback-controlled treadmill (treadmill-on-demand) and the spontaneous speed of walking and running in humans. *Journal of Applied Physiology 95*, 2, 838–843.

MOORE, D. S. AND MCCABE, G. P. 1999. *Introduction to the Practice of Statistics*. Freeman, San Francisco, CA.

MURRAY, M. P., SPURR, G. B., SEPIC, S. B., GARDNER, G. M., AND MOLLINGER, L. A. 1985. Treadmill vs. floor walking: kinematics, electromyogram, and heart rate. *J. Appl. Physiol. 59*, 1, 87–91.

NISE, N. S. 2004. *Control Systems Engineering*. Wiley, New York.

PELI, E. 2000a. Field expansion for homonymous hemianopia by optically-induced peripheral exotropia. *Optometry and Visual Science 77*, 9, 453–464.

PELI, E. 2000b. Augmented vision for central scotoma and peripheral field loss. In C., Stuen, A., Arditi, A., Horowitz, M. A., Lang, B., Rosenthal, and K. Seidman, Eds. Vision Rehabilitation: Assessment, Intervention and Outcomes. Swets & Zeitlinger, Lisse. 70–74.

PROFFITT, D. R., STEFANUCCI, J., BANTON, T., AND EPSTEIN, W. 2003. The role of effort in perceiving distance. *Psychol. Sci. 14*, 2, 106–112.

PROKOP, T., SCHUBERT, M., AND BERGER, W. 1997. Visual influence on human locomotion. *Exp. Brain. Res. 1997*, 114, 63–70.

RIZZO, M., FISHER, D., ANDERSEN, J., AND VAN WINSUM, W. 2005. CARSS Coordinated Assessment of Roadway Simulator Scenarios, *Simulator Users Group, Division of Neuroergonomics, Department of Neurology, University of Iowa*, Retrieved August 31, 2006 from http://www.uiowa.edu/~neuroerg/Simulator%20Users%20Group/carss%20scenarios%205%2018%2005.pdf.

SCHUBERT, M., PROKOP, T., BROCKE, F., AND BERGER, W. 2005. Visual kinesthesia and locomotion in Parkinson's Disease. *Movement Disorders 20*, 2, 141–150.

SOONG, G. P., LOVIE-KITCHIN, J. E., AND BROWN, B. 2004. Measurements of preferred walking speed in subjects with central and peripheral vision loss. *Ophthal. Physiol. Opt. 24*, 291–295.

THURRELL, A. E. I., PELAH, A., AND DISTLER, H. K. 1998. The influence of non-visual signals of walking on the perceived speed of optic flow (abstract). *Perception 27s*, 147.

WANN, J. P., SWAPP, D., AND RUSHTON, S. K. 2000. Heading perception and the allocation of attention. *Vision Research 40*, 2533–2543.

WELLS, M., PETERSON, B., AND ATEN, J. 1996. The virtual motion controller: a sufficient-motion walking simulator. In *Virtual Reality Annual International Symposium (IEEE '97)*, Albuquerque, NM. 1–8.

WILLEMSEN, P. AND GOOCH, A. A. 2002. An experimental comparison of perceived egocentric distance in real, image-based, and traditional virtual environments using direct walking tasks. In *Proceedings of the IEEE Virtual Reality 2002 (VR '02)*. 1–6.

WITMER, B. G. AND KLINE, P. B. 1998. Judging perceived and traversed distance in virtual environments. *Presence* 7, 2, 144–167.

WOODS, R., SHIEH, J., BOBROW, L., VORA, A., BARABAS, J., GOLDSTEIN, R., AND PELI, E. 2003. Perceived collision with an obstacle in a virtual environment (abstract). *Association for Research in Vision and Ophthalmology (ARVO CD). Item 4321*

WOODS, R. L., MANDEL, A. J., BARABAS, J., GOLDSTEIN, R. B., AND PELI, E. 2005. Making virtual reality more real and the perception of potential collisions (abstract). *Journal of Vision 4*, 8, 814–814.

WOODWAY. 2004. Woodway USA Treadmill Control Protocol (RS-232 Protocol, RS-232 port on the Display Board), Waukesha.

Received November 2005; revised August 2006; accepted December 2006