P-27: Maintaining Position and Display Perspective in a Walking Simulator while Self-pacing on a Treadmill

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Abstract

We developed a feedback controller for a walking simulator composed of a treadmill and a rear projection screen. The controller keeps the subject centered and visual extent consistent across subjects and throughout individual trials while allowing subjects to set their own walking pace.

1. Objective and Background

People with visual impairment (low-vision) are frequently prone to injury while walking, which makes testing low-vision aids for mobility in the real world difficult and potentially dangerous. Virtual environments (VEs) may be used for comprehensively testing low-vision aids while removing the danger of adverse events and providing a controlled environment that is repeatable and thus facilitates comparisons across conditions and between observers. VEs may also serve as platforms to test spatial navigation (way finding) and collision detection and avoidance.

Head-mounted displays are often used in VEs [7, 10], but these may interfere with head-mounted low-vision aids. As an alternative, a large rear-projection screen may be used in walking simulators in front of a treadmill. One limitation of rear-projection screens is the variability of their visual extents as the subject moves away from or closer to the screen. This is important for experiments that may need to maintain fixed level of peripheral stimulation across subjects (e.g. in optic flow experiments). A feedback system that keeps the user at a fixed distance from the screen will keep the visual extent of the screen constant.

Many VE studies visually simulate mobility without any physical action by the subject, who is standing or sitting [3, 14]. Physical movement by the subject has been shown to alter results for the perception of speed [6]. A number of walking simulators have been developed [4, 9, 15]. These systems are often costly because they include features that we do not need, such as support for running or the ability to simulate uneven terrain.

Several simulated locomotion devices are built around treadmills. Minetti et al. [11] reported a feedback-controlled locomotion interface (Treadmill-On-Demand) that was used for measuring walking and running speeds, but could be used in a VE. The user's position on the treadmill varied with the speed, and thus the controller would not keep a consistent distance between the user and the rear projection screen if the user changed walking speed. Hollerbach et al. [8] 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), which would keep screen extents consistent. In addition to centering the user, the mechanical tether applied inertial forces to provide the subject with a more natural experience during acceleration and deceleration. To avoid the high cost of the Sarcos Treadport system, others have used cheaper, smaller, conventional treadmills, moving at fixed speeds [2, 6]. Apfelbaum et al. [1] placed a bar in front of the subject to keep their position constant. This approach does keep the visual extents of the screen constant, but it does not allow the user to set and vary their walking speed naturally and an incorrectly chosen treadmill speed may cause fatigue.

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The self-propelled treadmill mode does keep the visual extent constant and allow the subject to adjust their walking speed. In such a configuration, the treadmill motor is disengaged and the subjects move the treads while pushing front handrails or are tied to ropes behind them [1, 5, 13, 16]. 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 tread for the duration of an experiment. Thus, data quality may degrade due to subject fatigue or the amount of data that can be acquired may be restricted. Maintaining a stable location across subjects in the self-propelled treadmill mode requires careful manual measurements and physical restraint of the subject (e.g., tethers). In addition the contact with handrail or ropes limits the natural body gait and may affect head position and movement.

We built a feedback-controlled locomotion interface that alters the speed of the treadmill motor in response to change of subject walking speed by maintaining the position of a sensor, worn by the subject, within a narrow region of our 164 by 55 cm treadmill. This interface allowed subjects on the treadmill to vary their walking speed in a natural way, to walk with no more exertion than natural walking, and to be repositioned automatically by the interface in order to maintain constant visual extent of the display. We compared the self-propelled and feedback-controlled modes.

2. Methods

2.1 Apparatus

Subjects walked on a Woodway Desmo S treadmill, similar to those found in a gymnasium (http://www.woodway.com). The treadmill drive is ball bearing based, so the self-propelled mode is easier than on the other brands of treadmill we evaluated. The treadmill was modified (in a reversible manner, see below), to allow computer control of the treadmill speed, rather than the supplied control panel.

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 PowerLite 9100i (http://www.epson.com) projector (Figure 1). The screen measured 172 by 127 cm, which provided 94 horizontal by 77 vertical degrees field when the subject was 80 cm from the screen.

A Flock of Birds Magnetic Tracker (http://www.ascension-tech.com) with two position sensors was used to monitor the subject's body position. One sensor was placed on the subject's head using a headband. Measurements from this sensor were used by the graphics workstation to compute virtual camera position (viewpoint) for generating views of the visual environment. The

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second position sensor is placed on the subject's hip, and was used by the feedback-controlled treadmill interface. We use hip position, and not head position measurements for the feedback-control system because hip position better reflects the user's center of mass: Controlling the treadmill with readings from the hip sensor makes the readings less prone to body movements that are independent of walking, such as turning or bobbing the head.

Self-propelled locomotion was implemented by having the motor disengaged while the subject walked on the treadmill that was set at a preferred incline. Using gravity, the incline reduced the amount of force necessary to push the treadmill tread backward. A rope anchored the subjects to the wall behind them to provide the additional force for treadmill movement

Various safety measures were implemented. Subjects were attached with a second rope to a PVC front rail, so that they would not slide off the back of the treadmill if they stopped walking while the treadmill belt continued to advance due to the incline and momentum. The operator running the experiment from a console was able to trigger an emergency brake during the feedback-controlled portion of the experiment (this was never necessary at any point in the experiment). The emergency brake disengages the motor, so that the treadmill belt will not move unless pushed manually. During all phases subjects also wore a safety harness, connected to the ceiling, for protection in case of a fall.

To implement the feedback-controlled treadmill interface, the following treadmill modifications were made:

2.1.1 Hardware

A controller board inside the Woodway treadmill, processes commands from the treadmill control panel. A motor driver board turns the control board's speed commands into an analog voltage that drives the motor. To control treadmill speed from the VE workstation, we implemented the Treadmill Interface Controller (TIC) as a two-way interface between the treadmill and the VE workstation by directly sending speed commands to the motor driver board using a serial port. The TIC counts pulses on the treadmill's internal tachometer and relays them to the workstation while sending speed commands that it receives from the workstation to the treadmill.

The treadmill has a large range of native speeds (15 mph in reverse to 15 mph forward). Since our anticipated subject population consists of walking elderly participants (and to increase safety), the TIC was limited to outputs of 0.7 mph in reverse and 6.8 mph forward. The software also imposes a maximum speed (4.0 mph) and did not allow the treadmill to go in reverse.

2.1.2 Software

The feedback-controller itself is a proportional-integral-derivative (PID) controller [12] implemented in software and run by the VE application. The VE application reads the hip-tracker and calculates the distance (x_{error}) between position sensor and intended position (x_0) along the treadmill (Figure 1). By keeping the subject close to x_0, we keep the visual extent of the screen nearly constant. The feedback-controller uses x_{error} to calculate the desired speed for the treadmill. The speed is a function of the current x_{error}, of the time integral of x_{error}, and of the time derivative of x_{error}.

The integral term is the actual mechanism that eventually brings the subject close to x_0. The integral term grows the longer the subject is away from x_0, which will gradually increase the treadmill speed in order to return the subject to x_0. This will reduce discomfort caused by abrupt treadmill movements, but allows overshoot, i.e. the feedback-controller initially allows users to go beyond x_0 during an increase in speed and does not attempt to correct this as quickly as it could. If users change speed frequently, they will spend more time away from x_0.

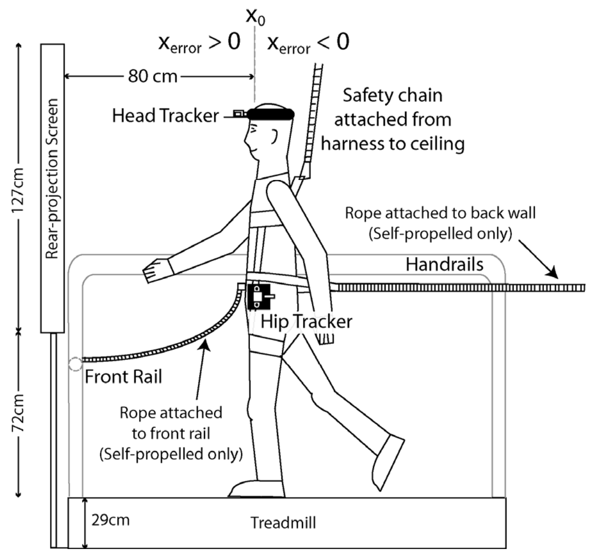

Figure 1 – Feedback-controlled treadmill setup. The speed of the treadmill is adjusted to keep the hip tracker at x_0. The distance from x_0, called x_{error}, is used by the feedback-controller to change the speed of the treadmill. In addition to automated safety controls of the treadmill, subjects wear a safety harness and have side handrails to protect themselves from a fall. Back and front ropes are used to provide anchoring in the self-propelled condition.

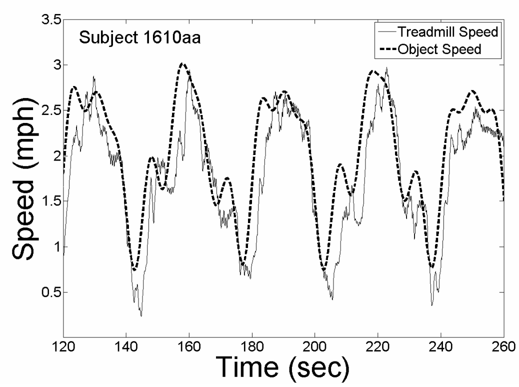

Figure 2 – The pseudorandom lead-object speed and the feedback-controlled treadmill speed as one subject performed a portion of a continuously changing speed-matching task.

Although the hardware supports putting the treadmill in reverse, the software prevented driving in reverse since pilot subjects said that it felt disconcerting. Therefore, sudden halts by the subject would result in them coming to rest where x_{error} is less than zero. Care is needed in dealing with overshoot during decelerations. 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.

Before sending a speed command to the treadmill, the feedback-control software makes several safety checks. The software checks that the subject stays within a specified three-dimensional safety zone (indication of a fall, stumble, or walking off the treadmill), checks that the sensor has not moved unexpectedly fast (indication of a fall), and sets the maximum speed to four miles per hour (we do not currently support running on the feedback-controlled treadmill). If any of these conditions are not met, the software automatically triggers an emergency brake (disengages the motor).

2.2 Experimental design

Six naïve subjects with normal sight participated in the study. Two were male and four were female. Their ages ranged from 21 to 60 years old (median: 33).

For each subject, we recorded a pulse rate before and after a five-minute walk on level terrain in the real world, on the self-propelled treadmill, and on the feedback-controlled treadmill. Each walk was done at the subject's preferred walking speed, which varied depending on the mode.

Additionally, subjects performed two speed-matching tasks for each of the two modes of treadmill locomotion, self-propelled and feedback-controlled. The feedback-controlled tasks were done on a different day than the self-propelled tasks, with the exception of one subject who took an hour break between the two series of tasks. The tasks were done in a random order with a different ordering in each of the two modes.

On the screen, the subjects were presented with a virtual mall corridor (an infinite corridor), which was composed of two 150-meter segments of a shopping mall hallway. The corridor seemed infinite since the segment behind the subject would be placed in front of the current one after the previous segment was passed. Sidewalls had photographs of storefronts and both the ceiling and floor were textured.

Before beginning the speed-matching tasks for each mode of locomotion, subjects were given a brief tutorial on how to walk on the treadmill for a given mode of locomotion. For the self-propelled mode, individual preferred inclines ranged from 4.5 to 11 degrees, with a median of 8 degrees.

In the speed-matching tasks the subject had to match the speed of a lead object (a trash can on wheels) that moved parallel to the subjects' direction of locomotion. In one task, the trash can would change speeds abruptly (between constant speeds that ranged from 0.5 mph to 3.5 mph) and, in the other, its speed was continuously changing pseudorandomly (the speed was composed of a summation of three sinusoids that ranged from 0.7 mph to 3.2 mph, but the trash can never accelerated or decelerated greater than 0.224 m/s^2 (0.5 mph/sec)) (Figure 2). The same sinusoid sum was used for all subjects in all of their continuous speed change tasks. Subjects were told to keep the trash can at a fixed distance in front of them for the entire task and a distance of about six of the infinite corridor's floor tiles was suggested. The two different speed categories allowed the analysis of large, sudden changes as well as gradual changes in speed.

After a subject completed all of the tasks for each of the two locomotion modes, the subject was asked to rank (-3 through 3) the level of physical exertion compared to walking normally. A rating of zero indicated that the mode of locomotion was comparable to walking. The subjects answered the questionnaire without being reminded of their responses for the other mode of locomotion.

3. Results

3.1 Subject positioning on the treadmill

In the feedback-controlled mode, each subject was kept within 1 cm of x_0 (on average), regardless of the task involved. For the self-propelled mode, accurate specification of average subject position on the treadmill across subjects was not possible. Due to the tethers and treadmill incline used in the self-propelled mode, the average position error was +15 cm from x_0 and ranged from +5 to +26 cm. That average position error could be reduced by more careful adjustment of the tethers. The poor results represent the difficulty in achieving such careful adjustment.

Table 1: Medians across all subjects of the deviation from average hip position on treadmill belt (in cm)

99^{th} Percentile

	Constant Speed*	Continuous Speed Changes	Abrupt Speed Changes
Feedback-controlled	8 (6%)	19 (15%)	25 (19%)
Self-propelled	4 (3%)	10 (8%)	27 (24%)

90^{th} Percentile

	Constant Speed*	Continuous Speed Changes**	Abrupt Speed Changes
Feedback-controlled	5 (4%)	13 (10%)	12 (9%)
Self-propelled	2 (2%)	3 (2%)	5 (4%)

Table 1- For each subject, the distance (in cm) from his or her average hip position was calculated for each frame, and two percentile values (99^{th} and 90^{th}) were found. The medians, across all subjects, of the deviation at these two levels were then taken. The corresponding changes in horizontal visual extent in parentheses assume an average position of x_0. The Constant Speed column is from the preferred walk with the initial acceleration and final deceleration removed. Time at rest was removed from the Abrupt Speed Changes data, since subjects come to rest behind x_0 and the feedback-controller did not correct this automatically. The '*' denotes a statistically significant difference (Wilcoxon Signed Rank Test) between the feedback-controlled and self-propelled modes at $p < 0.1$ and '' denotes significance at $p < 0.05$.**

In order to keep the visual extent consistent, the deviation of subject position from a set location (x_0 for feedback-controlled and the average subject position for self-propelled) should be minimized. For each subject, the 99^{th} and 90^{th} percentiles of this deviation, across all frames, were found. Table 1 shows the medians across all subjects of these deviation values. The self-propelled mode kept subjects in a smaller area on the treadmill than the feedback-controlled mode due to the back rope holding the subjects in a fixed position whenever they moved forward and the front rope preventing them from sliding back too far due to the incline. The large differences between the 90^{th} and 99^{th} percentile ranges suggest that much of the apparently large ranges for the speed-changing conditions were a consequence of the lags or leads that occurred during acceleration or deceleration.

3.2 Physical exertion

Answers to the questionnaire and differences in pulse rates between measurements, taken before and after the preferred walking speed tasks (Table 2), were used as measures of physical exertion. Compared to real world walking, the difference in pulse rates was not significantly different for the feedback-controlled mode (Wilcoxon Signed Rank Test $p = 0.69$), but was greater with self-propelled mode ($p = 0.03$). The difference in pulse rates was greater in the self-propelled than the feedback-controlled mode ($p = 0.03$). In the questionnaires, all subjects answered that there was more physical exertion necessary for the self-propelled mode (average score: 1.92; $p = 0.03$) and little (though not statistically significant) more physical exertion necessary with the feedback-controlled mode (average score: 0.42; $p = 0.25$) than while walking normally. In the comments section of the questionnaire, the high level of physical exertion was a common complaint among subjects about the self-propelled mode of locomotion.

Table 2: Average pulse rates (in beats/min) of preferred walking speed tasks

	Before	After	Difference
Real World	77 ±12	93 ±13	16
Self-propelled **	74 ±14	115 ±20	41
Feedback-controlled	79 ±15	90 ±12	10

Table 2 – Self-propelled resulted in the largest difference in pulse rates for all subjects. The '' is to denote that the self-propelled mode had a statistically significant ($p < 0.05$) mean difference from the other two modes.**

4. Discussion

The feedback-controlled treadmill interface was found to be safe (even on sudden halts from 3.5 mph to 0 mph), built from easily purchased components, required minimal training for use, allowed the user to walk in a natural manner with easy, voluntary changes in walking speed, required little or no more physical exertion than walking normally, and maintained the user at a fairly consistent distance from the display screen even with considerable changes in walking speed. Although visual extent varied less for individual subjects when using the self-propelled mode than the feedback-controlled mode, the visual extent across subjects was easier to keep consistent with the feedback-controlled mode, since no manual adjustment of tethers was required.

5. Impact

The feedback-controlled treadmill allowed subjects to walk with less effort and to control their own walking speed, which may improve their sense of immersion, while keeping the visual extents of the screen constant. With less physical exertion, experimenters will be able to collect more data before the subject fatigues.

6. Acknowledgements

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