

Robert R. Christensen
John M. Hollerbach
Yangming Xu
Sanford G. Meek
Mechanical Engineering Department
Computer Science Department
University of Utah
Salt Lake City, UT 84112
jmh@cs.utah.edu
www.cs.utah.edu/~jmh/
locomotion.html

Inertial-Force Feedback for the Treadport Locomotion Interface

Abstract

The inertial force due to the acceleration of a locomotion interface is identified as a difference between virtual and real-world locomotion. To counter the inertial force, inertial-force feedback was implemented for the Treadport, a locomotion interface. A force controller was designed for a mechanical tether to apply the feedback force to the user. For the case of the user accelerating forward from rest, psychophysical experiments showed that subjects preferred inertial-force feedback to a spring-feedback force proportional to position or to position control, where the force feedback maintained a force of zero on the subject.

1 Introduction

Conventional virtual reality solutions to user movement through virtual space generally involve position tracking with a variety of sensors that include mechanical, optical, acoustic, inertial, and magnetic sensors (Durlach & Mavor, 1994). In the simplest scenario, a joystick controls the movement through terrain or large structures of either a user's avatar or of some spacecraft, airplane, or vehicle. Some of the realism is lost in this artificial approach as movement is subjugated to manipulation or graphics realism (Witmer & Kline, 1998).

More-complex scenarios involve a user walking in a confined space and the tracking of the user's position. The Walkthrough Project tracks user position by cameras on a head-mounted visual display viewing light-emitting diodes embedded in the ceiling (Ward et al., 1992). The CAVE employs surround screens and magnetic sensors for user tracking (Cruz-Neira et al., 1993). Slater et al. (1995) investigated the use of walking in place for navigation in virtual environments. Peterson et al. (1998) employ a shallow disc that senses the direction of a user stepping from the center.

Another approach is whole-body motion platforms, in which a user is passively seated and moved through small excursions. Examples are flight simulators and vehicle simulators (Cremer & Kearney, 1995; Durlach & Mavor, 1994; Salcudean et al., 1994) that offer kinesthetic cues appropriate for these simulators. Yet, because the user is seated passively, the user does not expend energy in moving through virtual worlds.

Locomotion interfaces are energy-extractive interfaces to virtual environments and fill needs that are not met by conventional position-tracking approaches or whole-body motion platforms:

- They allow wide ranging in the virtual world in a limited space in the real world.

- They increase the user's involvement in the virtual world.
- They affect the decision-making process through fatigue and reflection of the virtual world's surface.
- They free the user to work with other VR appliances, such as position trackers, head-mounted displays, and so forth.

Possible applications for locomotion interfaces include:

- **Virtual design.** A designer can walk through architectural models, virtual assembly lines, and ship interiors.
- **Education.** Students can maneuver through historical sites, the moon surface, and insect colonies.
- **Training.** Individual training for the military, law enforcement, and fire fighting with virtual reality systems are more realistic when users are forced to expend energy to achieve goals.
- **Adversarial gaming.** Individuals can compete in organized arcades of locomotion interfaces or against computer-generated forces.
- **Health rehabilitation.** The systems can provide customized exercise and monitoring environments for those afflicted with mobility problems.
- **Exercise and recreation.** City-bound hikers may safely enjoy back-country rigors without leaving the confines of their living rooms.
- **Psychophysical research.** Sensorimotor integration and navigation issues can be studied through manipulation of the virtual environment, such as the gain between optical flow and locomotion (Rieser et al., 1995).

Several different types of locomotion interfaces have been previously developed.

1. **Pedaling devices.** The OSIRIS (Lorenzo et al., 1995) is a simulator for night-vision battle and employs a stair-stepper device. The Uniport (Sarcos Research, Inc.) is a unicycle with electrically actuated pedals that provide resistance based upon terrain slope and locomotion speed. Steering is achieved by twisting at the waist. Distler and Bulthoff (1996) employ a reclining bicycle with handgrips for steering in a CAVE environment.

Enzor and Carraro (1997) employ a bicycle with programmable pedal resistance. Brogan et al. (1997) employ an instrumented bicycle on a platform that can pitch 12 deg. to simulate the effect of going up or down hills.

2. **Programmable foot platforms.** Uneven terrain can be presented by active three-degree-of-freedom (DOF) platforms for each foot. The Sarcos Biport employs three-axis hydraulic serial-drive platforms for each foot. (Force sensing and control are required to unburden the foot during the swing phase.) Roston and Peurach (1997) report on an electrically driven three-DOF, two-foot platform system.
3. **Sliding surfaces.** Iwata has created several versions of devices that involve a stationary human sliding his or her feet over the "ground" during walking. In one version, a user wears rollerskates and is rigidly attached to a frame by a belt around the waist (Iwata, 1992). Foot forces for climbing or descending are created by a single string belt for each foot that is routed through pulleys to the bottom of each foot and actuated by a DC motor. More recently, Iwata and Fujii (1996) replace the rollerskates by shoes with low-friction films on the soles. A brake pad on the toe allows completion of the swing phase. The user is loosely constrained by a hoop frame.
4. **Treadmills.** Brooks et al. (1992) employed a passive or nonmotorized treadmill and instrumented bicycle handlebars for steering. Witmer and Kline (1998) also employed a passive treadmill. The ATLAS system (Noma & Miyasato, 1998) employs an active treadmill on a spherical joint; body motion is measured with a string potentiometer and by video tracking markers on the feet. The Sarcos Treadport employs a large, tilting, active treadmill and a horizontal mechanical tether to measure body movement and apply forces to the user for various purposes. Darken and Cockayne (1997) report on the use of the Omni-Directional Treadmill, a two-dimensional active treadmill that employs two orthogonal roller belts. A mechanical tracking arm on an overhead boom measures body position and

applies bias forces to center a user. Iwata (1999) drives a torus-shaped surface consisting of ten belts to generate an infinite surface.

1.1 Treadmill Locomotion

This paper is concerned with treadmill-style locomotion interfaces—and the Sarcos Treadport in particular. Treadmill-style locomotion interfaces support many human mobility activities:

- walking, running, shuffling, sprinting, and skipping
- moving backwards or forwards
- turning left or right
- sidling
- kneeling and crawling

A key issue is whether the treadmill is motorized. In nonmotorized or passive treadmills, because there is no motor, the belt motion is due to the forces applied to the belt by the user. The sensed belt speed is then used to update the user's position in the virtual environment. Unrestrained human mobility that involves walking or running results in highly variable energy utilization. Nonmotorized treadmills provide a fairly crude approximation to natural walking and running, however, with distortions from unnatural gait. A major problem with passive treadmills is that the belt's velocity is constantly changing. As the user's foot makes contact with the belt, it first slows the belt and then speeds it up as the foot pushes off. The belt then starts to slow down again due to friction, until the user's other foot strikes and the cycle repeats.

In active treadmills, measurements of user position are accomplished by optical tracking (the ATLAS system) or by a mechanical linkage or tether (Sarcos Treadport or Omni-Directional Treadmill). These measurements are employed to control treadmill speed and the movement of a user's avatar through the virtual environment. Turning in the ATLAS system is achieved by swiveling the treadmill about a vertical axis in the direction that the user is stepping. A two-dimensional treadmill allows a natural change of direction, although stability issues in walking on the roller surface of the Omni-Directional Treadmill have been reported (Darken & Cockayne,

1997). On the Sarcos Treadport, turning in the virtual world is accomplished by rate control based on the amount of sideways excursion when moving or on the amount of left-right body turning when stationary.

Aside from the naturalness of turning, another challenge for treadmill-style locomotion interfaces is to accurately simulate straight-ahead motion on the ground. Interestingly, ground locomotion and treadmill locomotion differ in a critical aspect. When the treadmill belt moves at a constant speed, running, walking, and crawling on the treadmill are the same as on the ground. However, when the treadmill belt accelerates, it applies a force to the user that would not be felt during natural locomotion on the ground. This force is an inertial force due to the acceleration of the belt.

The effect of the inertial force can be quite large as seen from the results of Frishberg (1983). Frishberg filmed five sprinters during a 91.44 m (100 yd.) sprint and recorded their velocity profiles. He then programmed a treadmill to match these profiles, and each subject repeated the sprint on the treadmill. The oxygen debt for treadmill sprinting was 36% less than sprinting on the ground. The large difference in energy expenditures in Frishberg's results was more than could be attributed to the lack of air resistance when running on the treadmill. The inertial force due to the accelerating treadmill allowed the subjects to use less energy.

Moghaddam and Buehler (1993) proposed to counteract this inertial force by varying the speed of the belt. Their application is a treadmill for research on legged robot locomotion. Because it is not possible to achieve exact compensation for the inertial force by varying the belt speed alone, they proposed an optimal scheme to control the belt's velocity that trades off differences in the contact forces and the velocity profiles between locomotion on the treadmill and on the ground. Simplified models for the user and the system were employed: the human was modeled as a wheeled cart with a velocity-feedback controller. Step inputs to the cart were studied to simulate acceleration to a maximum velocity.

Flight simulators employ another method to simulate the forces felt during acceleration. The entire simulator tilts to change the angle of the force felt by the pilot, so that a fraction of the gravitational force is used to simu-

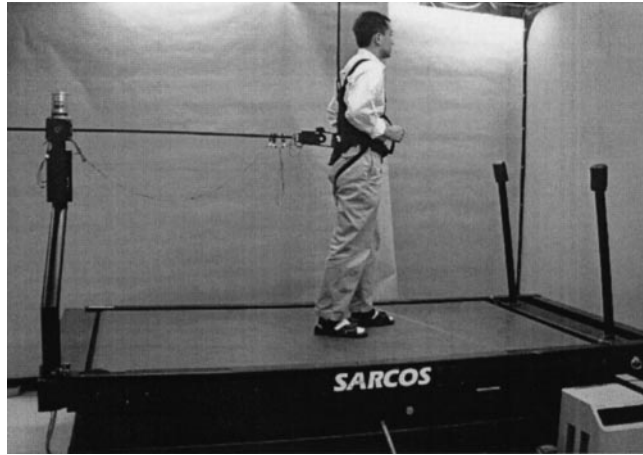


Figure 1. *The Treadport.*

late limited acceleration. The advantage of this method is that the force is applied to the pilot's whole body. While this method works well for flight simulators, when applied to a locomotion interface it has the disadvantage of confounding slope and acceleration. A tilting surface would provide kinesthetic cues to the user from the change in the angle of the ankle. There is also a practical implementation issue of changing the slope of the motion platform quickly enough because of its mass. A practical method that maintains the independence of slope and inertial force would be ideal (Tristano et al., 1999).

In this paper, we use the active mechanical tether on the Sarcos Treadport to achieve exact compensation of the inertial force, and we show through user studies the naturalness of this inertial-force feedback.

1.2 The Sarcos Treadport

The Sarcos Treadport (Figure 1) comprises a large commercial treadmill (4×8 ft), a six-DOF mechanical tether, and a CAVE-like visual display. The mechanical tether (Figure 2) is a key feature of this locomotion interface. Kinematically, the mechanical tether comprises a Hookean joint at the base, a prismatic joint (which is the primary joint adjusting for user travel), and a spherical joint attached to a climber's harness (Figure 3) worn by the user. The prismatic joint is actuated through a timing belt drive, which allows it to exert an axial horizontal force on the user. The harness worn by the user consists

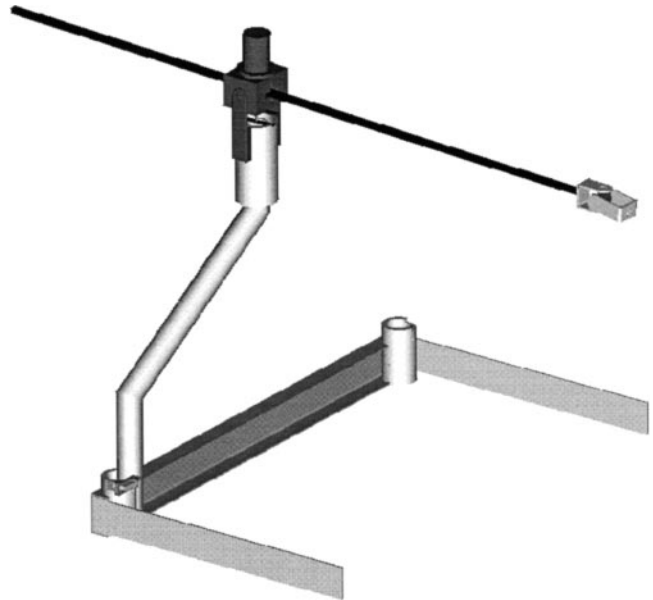


Figure 2. *The Treadport's mechanical tether.*

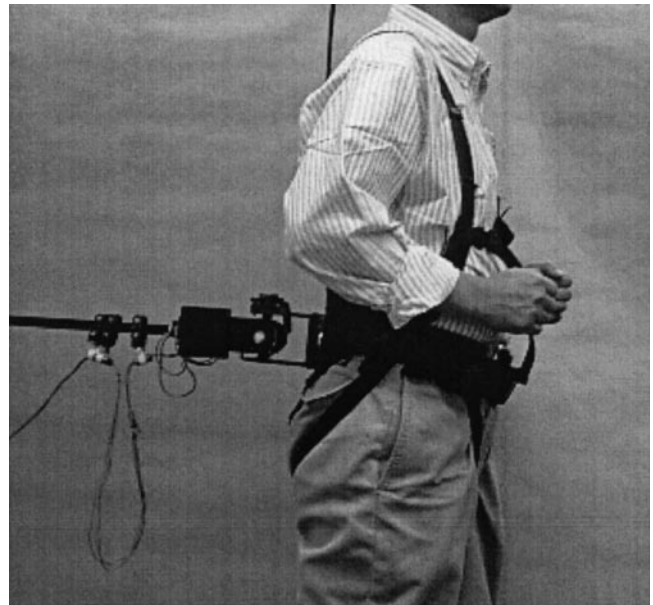


Figure 3. *The Treadport's harness.*

of a solid piece of material along the user's back, adjustable leg and shoulder loops, an adjustable belt, an adjustable chest strap, and adjustable height straps between the chest strap and belt. The tether is attached to a small plate in the back of the harness located in the small of

the user's back. Since its location is between the belt and the chest strap, it isn't possible to get the tether attachment coupled tightly to the body.

The harness is attached to the ceiling by a mechanism similar to an automobile seat belt. The safety line prevents sudden vertical accelerations. If the user were to trip and fall, the safety line would catch him. As long as the user doesn't move too quickly, the safety line would allow the user to bend down, squat, or crawl on his hands and knees. The tether is mounted behind the user and has a breakaway pin in case the user falls off the back of the treadmill. In this case, the treadmill would automatically stop the belt and turn off the tether. The treadmill also automatically stops if the user moves too close to the front of the treadmill.

The mechanical tether serves two general purposes. First, it acts as a position tracker to control the treadmill according to the user's motion and to change the graphical display. More uniquely, it exerts force on the user which can be employed for several purposes:

1. providing a centering force as a kinesthetic cue to help the user stay centered on the treadmill;
2. enforcing unilateral constraints by imposing a penalty force when a user attempts to walk through a virtual wall; and
3. pulling or pushing on the user to simulate the effects of gravity (Tristano et al., 1999) or uneven terrain.

Section 2 identifies the inertial force due to the acceleration of the treadmill belt as a difference between virtual and real world locomotion. Section 3 details the design, simulation, and implementation of the tether controller that provide force feedback to cancel the inertial force. Section 4 presents psychophysical experiments that were conducted to determine whether subjects preferred inertial-force feedback to other types of control. Conclusions are drawn in Section 5. Portions of this work have been previously reported (Christensen et al., 1998).

2 Virtual versus Real-World Locomotion

When an automobile accelerates forward, the passengers "feel" a force pushing them back into their seats. This imaginary force is known as an inertial force

and is due to the acceleration of the vehicle, which is the user's frame of reference. To an observer on the ground, it is apparent that the passenger is accelerating forward and the car seat is applying a force to cause this acceleration. The inertial force creates a difference between virtual and real-world locomotion. Consider a very large treadmill moving at a constant velocity with no external visual cues. A person on the treadmill would have no way to know the treadmill's speed or direction with respect to the ground—or even if it is moving at all. No matter what direction or speed the person would move relative to the treadmill, it would feel the same as on the ground. As long as the treadmill moves at a constant velocity, it is an inertial reference frame, and Newton's laws of motion apply.

If the treadmill belt were to suddenly accelerate, the user would feel as though he were pushed in the opposite direction of the acceleration. This inertial force is due to the acceleration of the reference frame. The treadmill belt is now a non-inertial reference frame because it is accelerating. For a non-inertial reference frame, if the inertial force is considered as an additional external force acting on the system, then it is possible to apply all the results and principles derivable from Newton's laws of motion relative to an inertial frame (Greenwood, 1988). The inertial force is in the opposite direction of the acceleration of the belt, and its magnitude is equal to the mass of the user multiplied by the belt's acceleration.

This large treadmill represents virtual locomotion. In order to analyze virtual locomotion in the same manner as real-world locomotion, the inertial force due to the acceleration of the belt must be considered. To illustrate this concept, consider simplifying the dynamics of the human by replacing them with those of a motorized, wheeled cart (Moghaddam & Buehler, 1993). The cart on the ground, or the real world, has the following dynamics:

$$f_g + f_f = ma_g, \quad (1)$$

where f_g is the contact force between the cart and the ground, f_f represents any aerodynamic friction forces, m is the mass of the cart, and a_g is the acceleration of the cart with respect to the ground.

The cart's motion is analyzed with respect to a coordinate system attached to the ground. The cart on the treadmill, or the virtual world, has these dynamics:

$$f_c + f_f = ma_{c/b} + ma_{b/g}, \quad (2)$$

where f_c is the contact force between the cart and the belt, $a_{c/b}$ is the acceleration of the cart with respect to the belt, $a_{b/g}$ is the acceleration of the belt with respect to the ground, and $ma_{b/g}$ represents the inertial force due to the acceleration of the belt.

The cart's motion is analyzed with respect to a coordinate system attached to the treadmill belt. By considering the inertial force as an additional external force, the equation can be rewritten as

$$f_c + f_f - ma_{b/g} = ma_{c/b} \quad (3)$$

For virtual and real-world locomotion to be the same, a given input should produce the same output in either system. That is, if the cart produces the same force profile on the ground and on the treadmill, then its acceleration and velocity profiles should be the same in the respective coordinate systems. This is analogous to a human sprinting from a standstill with maximum effort. Assuming that the difference in friction forces due to air resistance and in the different types of surfaces is negligible, the sprinter should have the same acceleration and velocity profiles in the virtual and real worlds. By comparing Equation (1) and (3), it can be seen that—if the contact force, the frictional force, and the acceleration with respect to the coordinate system are all the same—the equations are not equal unless $ma_{b/g}$ is zero. This term is due to the acceleration of the treadmill belt and is not zero because, if the treadmill belt does not accelerate, the user will run off the front. The inertial force direction is the same as the acceleration direction of the runner, so it is providing a force that helps the runner accelerate. This inertial force helps explain Frishberg's results.

Moghaddam and Buehler (1993) developed a controller for the treadmill belt's velocity to minimize the effect of the belt's acceleration. The effect cannot be eliminated through the control of the treadmill belt, and it is more pronounced with smaller treadmills and larger accelerations by the user.

The Treadport provides a solution to this problem

Display Screen

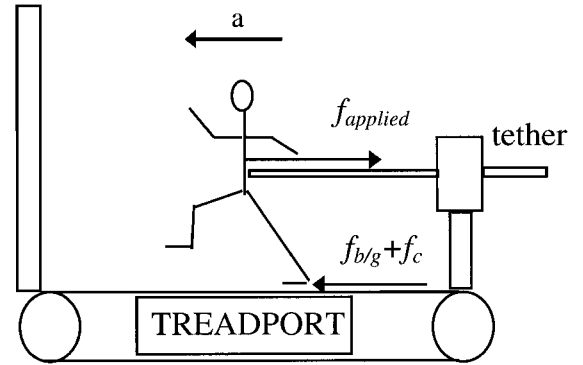


Figure 4. External forces during forward acceleration.

with force feedback from the mechanical tether. Equation (4) shows $f_{applied}$ as the feedback force.

$$f_c + f_f - ma_{b/g} + f_{applied} = ma_{c/b}. \quad (4)$$

If the magnitude of $f_{applied}$ is equal to the magnitude of the inertial force but in the opposite direction, then those two forces cancel, leaving

$$f_c + f_f = ma_{c/b}, \quad (5)$$

which is identical to the dynamics of the cart on the ground. The desired force to be applied by the tether in order to cancel the inertial force due to the acceleration of the belt is

$$f_{applied} = ma_{b/g}. \quad (6)$$

The application of this force is called inertial-force feedback. At this point, frictional forces are dropped from the analysis because this study is concerned with simulating the inertial force and not air resistance. The differences between treadmill and overground running recorded by Frishberg (1983) were much larger than could be attributed to air resistance. Figure 4 shows a runner accelerating on the Treadport. The external forces acting on the runner are the interaction force f_c , the inertial force $f_{b/g} = -ma_{b/g}$, and the applied tether force $f_{applied}$. Inertial-force feedback will use the tether force to cancel the inertial force, leaving only the interaction force which is the same as it would be on the ground.

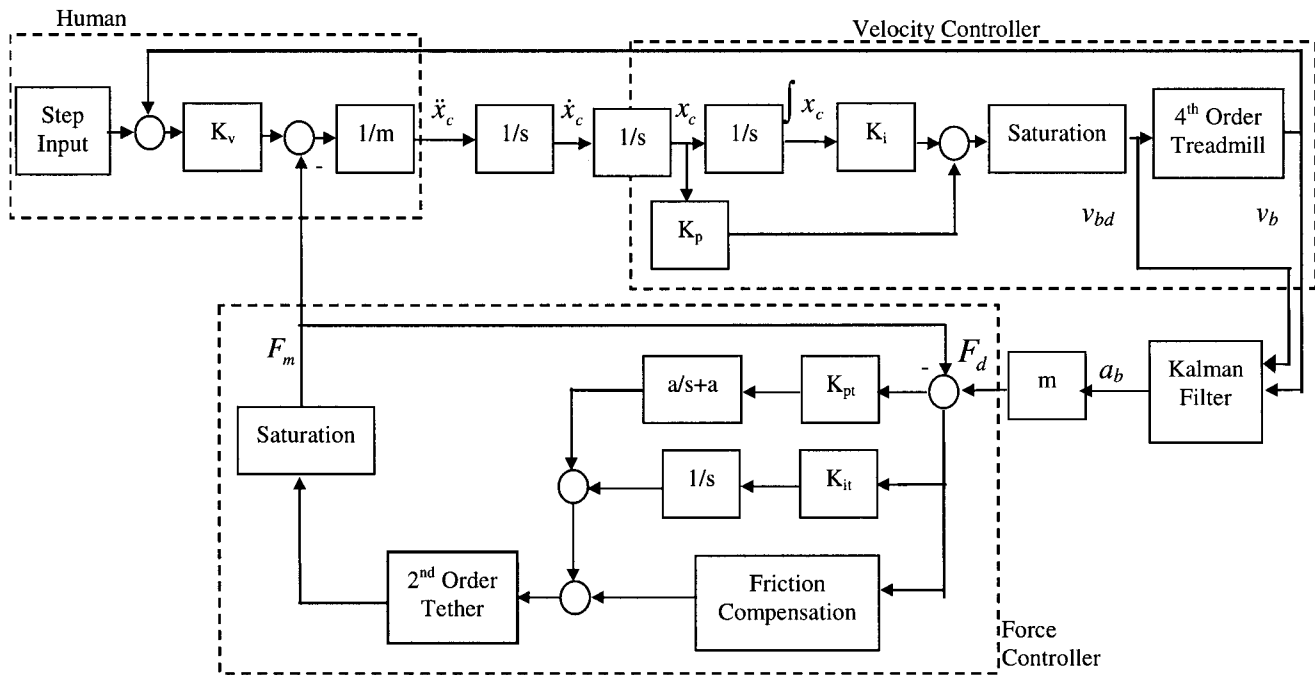


Figure 5. Treadport controller.

3 Control of the Treadport

The Treadport controller, as shown in Figure 5, consists of three parts: the velocity controller, the tether controller, and the model of the human subject. Controllers were designed for the force-feedback tether and the velocity of the treadmill belt. The purpose of the tether force controller is to cancel the inertial force due to the belt's acceleration. At the same time, the belt's velocity controller is needed to keep the user safe and to decrease the inertial force. As part of the process of designing the controllers, a model of human running was required. The three parts of the Treadport control scheme are discussed in the following sections.

3.1 Running Model

Hill (1927) derived an equation that describes rather accurately the sprint velocity curve of a sprinter (Henry & Trafton, 1951). This velocity equation is

$$v = v_m(1 - e^{-k_v t}), \quad (7)$$

where v is the velocity of the runner, v_m is the maximum velocity the runner is approaching, and k_v is a reaction

velocity constant. The interaction force was assumed to be constant instead of cyclical with each step. This model agrees with the model of a wheeled cart with a feedback velocity controller assumed by Moghaddam and Buehler (1993). The human running model is shown in the upper left block of Figure 5.

To determine the validity of this model, the sprint starts of five subjects were filmed. A film digitizer was used to determine the position and time data of retro-reflective markers attached to the subjects. Equation (7) was integrated to give the position of the runner:

$$x = v_m \left(t + \frac{e^{-kt}}{k} - \frac{1}{k} \right). \quad (8)$$

Equation (8) was fit to the data to determine the acceleration parameters to use in the simulations. Figure 6 shows the data and fitted equation for a typical sprint start.

3.2 Tether Control

The tether is chain-driven by a DC motor. A load cell is at the end of the tether where it attaches to the

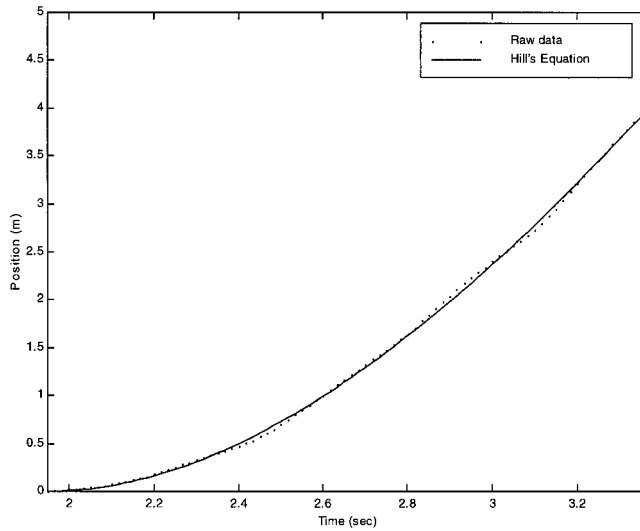


Figure 6. Position of an accelerating runner on the ground.

harness. The tether is capable of producing a sustained force of nearly 190 N. The open-loop frequency response of the tether was found using Siglab (DSP Technology, Inc.). The tether was analyzed by swept-sine analysis of the input voltage to the force sensor output while its position was constrained. Data were collected for several different input amplitudes. A second-order model was fit to the data and used in the simulations.

A force controller similar to that used by An et al. (1988) was used for the tether. A simplified block diagram of the system is shown in Figure 5, where v_{bd} is the desired treadmill belt velocity, v_b is the actual velocity of the belt, a_b is the estimated acceleration of the belt from the Kalman filter, F_d is the desired tether force, and F_m is the measured tether force. The control algorithm was implemented digitally at 400 Hz, and the servo rate was verified with a digital oscilloscope.

The force servo loop was tested while its position was constrained. Figure 7 shows the force step response of the tether while its position was constrained. Steps are a qualitative test for the stability of the tether, but a more realistic performance test is sine-wave command following (An et al., 1988). The next test was to follow a sinusoidal input while the position was constrained. The responses to the sinusoidal inputs are compared in Figure 8. The tether tracks the sine wave up to 10 Hz, although

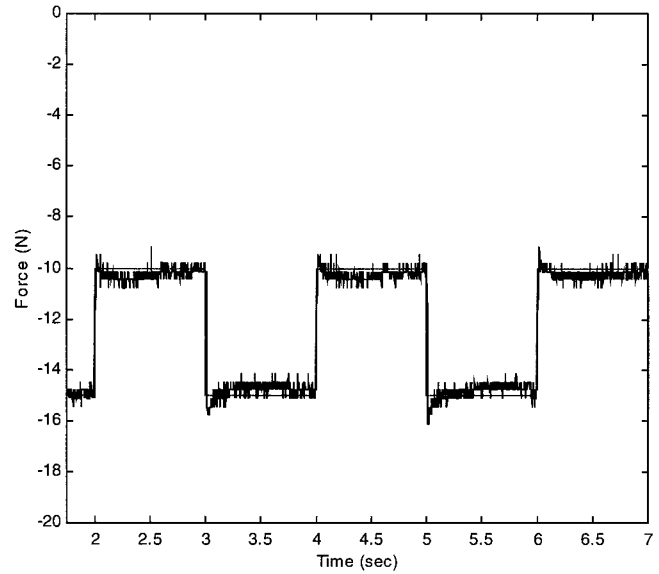


Figure 7. Experimental force controller step response.

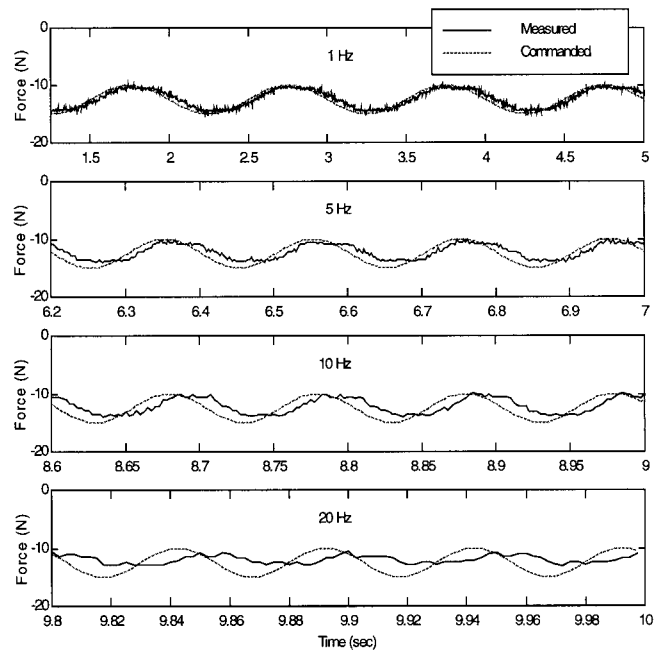


Figure 8. Experimental force controller sine response.

there is considerable lag. The bandwidth measured in this manner is at least 10 Hz.

When the force controller was implemented on subjects, the harness attachment was loose and caused back-

lash, the position was no longer constrained, and the user created disturbance forces. All of these factors impaired the performance of the tether force control. The actual inertial-force feedback had much more tracking error than the simulations, but its overall behavior was still acceptable.

3.3 Treadmill Control

The commercial treadmill includes a built-in velocity controller. Its frequency response was characterized with a Hewlett Packard 3562A Dynamic Signal Analyzer. Swept-sine analysis was done at several different input amplitudes. More tests of the system were completed using Siglab. Burst random noise was the stimulus to the system for different input amplitudes and bandwidths. It was found that a fourth-order model fit the data, and this model was subsequently used in the simulations and in the acceleration filter.

Figure 5 shows the velocity control scheme for the Treadport. The desired velocity command for the treadmill belt is derived from a proportional-integral (PI) controller based on the user's distance from an equilibrium point, as shown in Equation (9):

$$v_{bd} = k_p x + k_i \int x dt \quad (9)$$

the user's distance from the equilibrium point is x , k_p is the proportional constant, and k_i is the integral constant. The proportional term increases the speed of the treadmill as the user moves farther away from the equilibrium point. The integral term increases the speed of the treadmill the longer the user is away from the equilibrium point.

The integral control is important for the safety of users because it recenters users whenever they are moving at constant velocity. Without the integral control, a user's position would just be proportional to the velocity. Consider a subject who accelerates to $0.5 * v_m$, where v_m is a subject's maximum speed. Suppose that, after running at this speed for a while, the subject suddenly accelerates to v_m . If the velocity control did not have an integral term, the subject would already be close to the front of the treadmill. If there were enough delay in the treadmill's response, the subject could step off the front of

the treadmill and be injured. Integral control would have recentered the subject after the initial acceleration, and the Treadport would have had time to respond to the second acceleration.

If the treadmill were controlled so that the user was perfectly centered at all times, a fairly high inertial force would have to be applied by the tether. For example, a typical peak acceleration for a runner is approximately 10 m/s^2 . For a person weighing 75 kg , the tether would have to apply a force of close to 750 N . If, on the other hand, a user were allowed to move forward on the treadmill, the user would experience some actual acceleration that would reduce the force requirements on the tether. If the treadmill were very long, the belt could accelerate very slowly and the tether would need to apply less force. For a realistic treadmill, a user could be allowed to accelerate somewhat close to the front edge to reduce the tether force requirements.

Simulations were run to determine the integral and proportional gains for the velocity control of the belt so that the user nearly reaches the front of the treadmill during maximum acceleration. The simulations employed the runner's model and the treadmill model discussed earlier. Figure 9 shows the simulation results for the subject's position during maximum acceleration on the treadmill using the acceleration parameters from Equation (8). To minimize acceleration, it was decided to start subjects approximately 0.4 m behind the center of the treadmill. This reduced the required inertial force for forward acceleration and still allowed subjects to slow down and stop in a normal fashion. Figure 9 also compares the velocity profiles (on the ground and on the treadmill) and the interaction forces. The simulations show that the velocities and contact forces are almost exactly the same on the ground as they are on the Treadport. Figure 10 shows the commanded tether force and belt velocity on the Treadport.

The acceleration of the treadmill belt was needed to calculate the proper inertial force. The built-in velocity controller of the treadmill provides an output with the velocity of the treadmill. The data from this output were very noisy, and calculating acceleration from this data required filtering, which introduced lag that was too great to use to implement the inertial force. To solve this

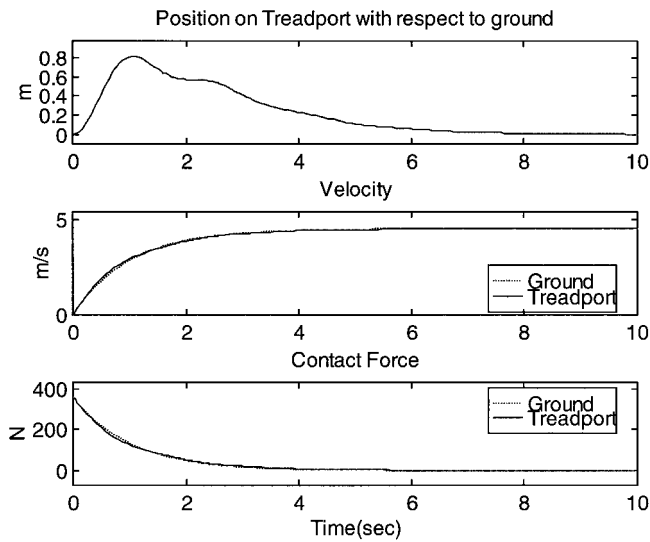


Figure 9. Simulated position, velocity, and interaction force during acceleration on the treadmill.

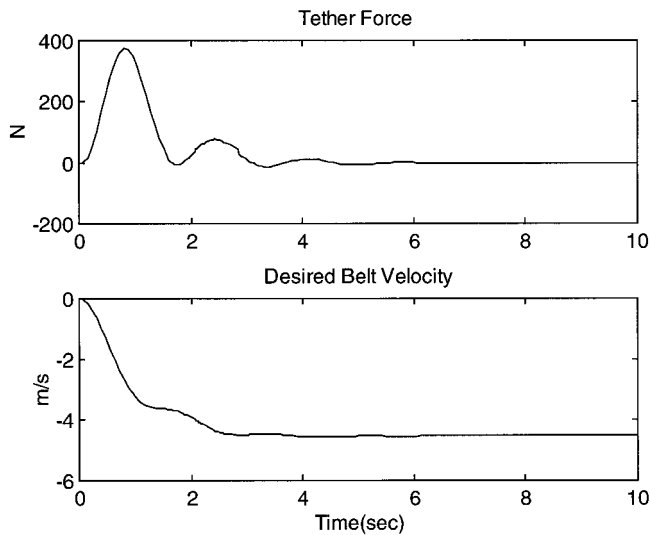


Figure 10. Simulated commanded tether force and belt velocity.

problem, a Kalman filter was used to estimate the acceleration. The inputs into the filter were the desired velocity and the velocity from the sensor. The fourth-order model of the treadmill was used in the filter.

3.4 Effect of Saturation

The simulations showed that the inertial force feedback would make the velocity profiles and interac-

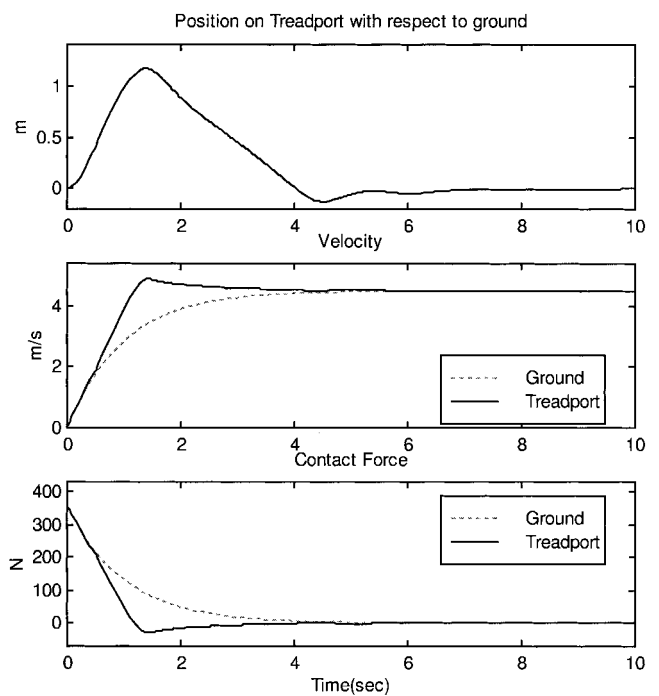


Figure 11. Simulated position, velocity, and interaction force during acceleration on the treadmill, with saturation.

tion forces exactly the same on the ground as on the treadmill. However, Figure 11 shows the same simulation with the maximum force limit of the tether (190 N) included. Also, the maximum velocity was limited to 5 m/s for safety reasons. Due to these saturations, the simulated results on the Treadport do not match exactly with those on the ground. Because the tether force is limited, it does not slow the user enough, so the velocity and contact force on the Treadport both overshoot the ideal curves for on the ground. Figure 12 shows the commanded inputs with saturation.

4 Psychophysical Experiments

The dynamics behind the new control algorithm were developed using a model of a cart with a velocity feedback. To test if users preferred this new dynamics-based algorithm, several comparisons were made through psychophysical experiments. Three tether force strategies were compared:

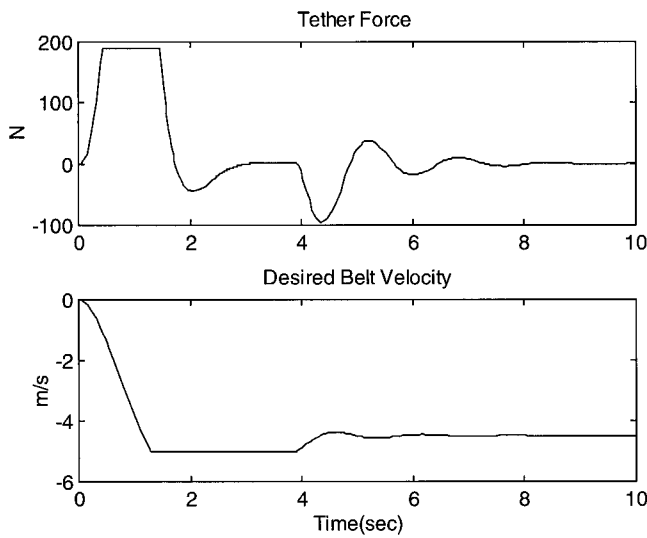


Figure 12. Simulated commanded force and velocity, with saturation.

1. **Zero force.** The tether controller attempts to maintain zero tether force on the user, and the user's position controls the velocity of the Treadport.
2. **Spring force.** The Treadport has been used successfully for many demonstrations without inertial-force feedback. The control scheme used thus far applies a spring force proportional to the user's position; its purpose is to provide a kinesthetic cue as to the middle of the treadmill. This spring force has been tested with many users and has been tuned to satisfy them. The force is not dependent upon the user's mass.
3. **Inertial force.** The tether force's magnitude is proportional to the product of the user's mass and the belt's acceleration. The force is in the same direction as the belt's acceleration.

Eleven subjects volunteered to participate in the psychophysical experiments. There were three female and eight male subjects ranging from twenty to fifty years old and 48 to 90 kg. Each subject was given instructions and then allowed to warm up and become accustomed to the Treadport. The subjects were told they would be comparing two different controllers at a time and would have to pick the one that felt more realistic. They were instructed to start each trial from rest and then accelerate as quickly as they felt comfortable. Once they reached a final velocity, they were asked to maintain it

Table I. Preferences in Psychophysical Experiments

Subject	Mass (kg)	Preferred control algorithm	Preferred percentage of force
1	75	Inertial force	60
2	90	Inertial force	80
3	84	Inertial force	80
4	73	Inertial force	100
5	73	Inertial force	100
6	59	Inertial force	60
7	77	Inertial force	80
8	86	Inertial force	100
9	72	Inertial force	80
10	52	Inertial force	100
11	48	Inertial force	80
Median	73	Inertial force	80

for several seconds and then to gradually slow down until they were stopped. At least two accelerations were done for each controller, and the subjects were allowed to change between the two controllers until they could make a decision.

In preliminary testing, some subjects preferred a fraction of the inertial force instead of the whole amount. This could be due to the differences between the cart model and the actual human dynamics. Another factor could be that inertial force is distributed over the entire body, while the equivalent tether force is concentrated at one point. To address these initial observations, comparisons were made of acceleration with different percentages of the inertial force feedback: 60%, 80%, and 100% of the inertial force. The two subjects who chose 60% were also allowed to experience 40% of the inertial force. Neither of them preferred this lower force, and it was not tested on any of the other subjects. Table 1 shows that, on average, subjects preferred 80% of the inertial force. The inertial force percentage that a subject chose was then employed in comparison to the zero-force and spring-force tether controllers.

During the psychophysical experiments, subjects were instructed to accelerate as quickly as they felt comfortable. One subject accelerated to approximately 4.5 m/s, which is near the current safety limit of the treadmill.

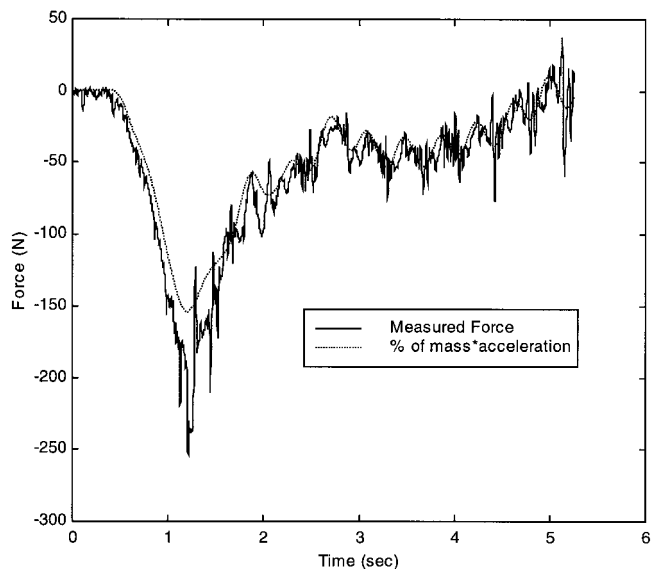


Figure 13. Actual force tracking of the tether during acceleration.

Simulations had shown that subjects should be started 0.4 m behind the center of the treadmill. In one of his initial starts, the subject was accidentally started in the middle of the treadmill. He accelerated quickly enough to come too close to the front and trip an emergency switch. In this situation, an emergency shutoff automatically stops the belt, and the tether's power is turned off. The subject was safely stopped before he ran off the front of the treadmill and into the rear-projection display screen. After this, he was started in the proper position. The remainder of his trials went smoothly. This shows that the simulations based on the human motion parameters agreed well with experimental data.

Table 1 also shows the preferences of the subjects from the psychophysical testing. All subjects preferred inertial-force feedback, then spring force, and then no force. Subjects preferred 80% of the inertial force instead of the full force. It was observed that the no-force strategy made the treadmill locomotion practically unstable, and subjects moved very tentatively.

Figure 13 shows real data during forward acceleration of a subject on the Treadport with inertial-force feedback. The solid line is the force measured by the load cell, and the dashed line is the commanded force, which is 80% of the product of the user's mass and the acceleration of the treadmill. The data have the opposite sign of

the simulations due to the data acquisition. Although the tether motor cannot produce a steady force of over 190 N, the force sensor measured larger forces. This occurs because the tether motor cannot move the tether fast enough, so the subject is also pulling the tether. Note the high-frequency content of the measured force due to the backlash in the tether connection.

5 Discussion

This paper identified a difference between locomotion on the ground and locomotion on a treadmill to be the inertial force caused by the acceleration of the treadmill. A controller was proposed for the Treadport to cancel the inertial force with a force applied by a powered tether. Simulations using simplified models showed that this controller should cancel the inertial force. However, the actual implementation did not cancel the inertial force as well as the simulations, mostly due to the backlash of the tether-to-harness connection. Psychophysical experiments were conducted to determine whether users preferred this theoretical control. The inertial force was chosen unanimously over spring force and zero force.

Subjects preferred 80% of the inertial force instead of the entire force. A possible reason for this preference could be due to the fact that the inertial force is distributed over the whole body and the force feedback is concentrated at the harness contact points.

The results indicate that inertial-force feedback causes a definite improvement, a finding that is supported by two cases. First, the psychophysical experiments show that users prefer inertial-force feedback to a spring force and no force. Second, the results of Frishberg (1983) show that, without inertial force, there is significantly less energy extraction during acceleration.

Future work should pursue several ideas in this area. In this paper, the preferred inertial force was found for each user and then compared to a spring force. Although this spring force had been chosen by trial and error with different subjects when the Treadport was first developed, it was not presented to the subjects in this test as often as inertial control was. Nor was it indi-

vidually tuned to each subject. This could have caused a bias towards inertial control. An improved experiment would be to find the average inertial force and spring force preferred by users and then test these two control schemes against each other. Future research is also planned in other tasks besides acceleration from rest.

A new Treadport being built at the University of Utah will include a larger treadmill and a more powerful tether. Improvements in actuation and sensing should allow for even better results.

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