# Validation of Torso Force Feedback Slope Simulation through an Energy Cost Comparison

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## Abstract

*This paper compares the energy cost of locomotion on a real slope and on a simulated slope using a tether force on the Sarcos Treadport. Walking and running both up and down slopes are investigated. Horizontal tether forces were based on $f = Kmg\sin(\theta)$ to simulate the slope $\theta$. For uphill walking and running, average values of K were determined to be 0.84 and 0.78. For downhill walking and running, average values of K were determined to be 0.72 and 0.66. These values of K reinforce previous findings from psychological and biomechanical studies that found K equal to an average of 0.65.*

## 1. Introduction

One goal for locomotion interfaces is to allow a human to experience a wide variety of geographic locations and interact appropriately with them. This includes walking and running up and down hills, mountains, and stairs. The Sarcos Treadport (Fig. 1) has been used to render these locomotion aspects using an active mechanical tether connected to a human [9,11].

The Sarcos Treadport consists of a large tilting treadmill, an active mechanical tether, and a 180-degree CAVE-like display [10]. The large 6-by-10 foot belt area provides the user with a high degree of maneuverability.

The most unique aspect of the Treadport is the active mechanical tether. The tether's linear axis is able to push or pull on the subject. These forces can be used to simulate unilateral constraints, slope [9], and inertial forces [5]. Sensors on the tether's six degrees of freedom provide the computer with feedback on the user's position. The computer then uses this information to calculate the speed of the belt and the rate at which the subject may be turning. Inertial forces are also calculated based on the belt's acceleration.

Belt speed can also be determined by the user. The tether senses how far forward from center the subject moves and the system responds by trying to re-center the subject. As the subject increases in speed, the belt naturally flows. The tether is the Treadport's haptic interface, connecting the human participant to the virtual world and making locomotion very natural, even when on an incline.

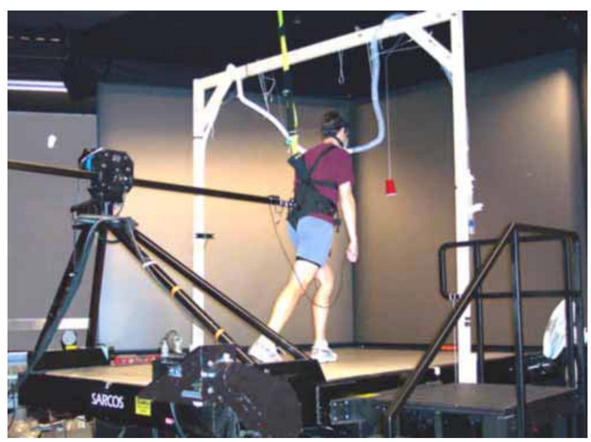


**Fig. 1.** The Sarcos Treadport with equipment for measuring oxygen consumption.

Simulating slope through the tether force has been shown to be an effective method of rendering smooth inclines on the Treadport. Hollerbach et al. [9] demonstrated that torso force feedback could be used to replace treadmill tilt. When walking on a slope of $\theta$ degrees, the force parallel to the slope that aids or hinders walking is: $f(\theta) = mg\sin\theta$. A slope can be

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rendered by keeping the treadmill level and then applying the force $f(\theta)$ to the user.

Substituting the tether force for actual tilt was validated by psychological and biomechanical experiments. For the psychological experiments, subjects walked on a sloped treadmill for one minute. The treadmill was then leveled and a corresponding tether force was applied to the subjects. The magnitude of the force was changed according to each subject's directives to best match the effort of the actual slope. The subjects preferred a reduced force of approximately $0.65mg\sin\theta$ rather than the full $mg\sin\theta$. For the rest of this paper the tether force will be referred to as $f = Kmg\sin\theta$, where different values of $K$ will be used to correlate simulating the actual slope $\theta$.

A similar experiment was conducted to compare the biomechanics between real and rendered slopes. Hip angle ranges were determined for subjects walking on slopes ranging from –6 degrees to 14 degrees in 2 degree increments and with tether forces ranging between -100 N and 60 N in 15 N increments. A negative force represented an uphill (pulling) force and a positive force represented a downhill (pushing) force. It was found that hip ranges on the actual slope most closely correlated with a value of $K$ equal to 0.64 ± 0.10 (SD).

Both the psychological and biomechanical experiments supported the conclusion that a reduced tether force of approximately $0.65mg\sin\theta$ created the most realistic simulation of slope. Another comparison between real and simulated tilt could be performed using the rate of oxygen consumption ($\dot{V}O_2$).

Research has already been conducted to measure $\dot{V}O_2$ for walking and running with applied horizontal forces [3,8]. However, this data supports a value of $K$ close to 1.1 to match the energy cost on actual slopes and thus, disagrees with the previous findings near 0.65 for $K$. Conducting a new experiment on the Treadport is necessary to determine whether the value of $K$ should support the previous value near 0.65 or the larger value of 1.1 using an energetic cost comparison. This new experiment will also investigate running on the Treadport, which has not been done previously to determine a value for $K$.

## 2. Methods

### 2.1. Experimental design

An experiment was designed to measure the energy cost for locomotion on different slopes and for different applied tether forces with no slope. After obtaining local ethical approval, seven subjects were selected for the experiment based on their physical fitness and abilities. Five of the subjects were male and two were female [age = 36.14 ± 12.75 (SD) yr, height = 1.77 ± 0.10 m, mass = 69.40 ± 9.26 kg]. Most of the subjects were marathon runners and had a high level of endurance. A high level of endurance was necessary to enable the subjects to run uphill long enough to obtain an accurate $\dot{V}O_2$ measurement without exceeding their aerobic capacities.

Multiple sessions (6-7) were required for each subject to complete the experiment. During the first session the subject was weighed and fitted with a proper facemask. The subject was then placed on the Treadport and harnessed to the active tether (fig. 1). The subject underwent a ten-minute routine to help them become habituated to the Treadport and facemask.

The experiment consisted of measuring each subject's oxygen consumption while walking and running at different slopes and while applying different tether forces. The deck was level during the application of any tether forces. Slopes varied between ±15 degrees in 3-degree increments. Tether forces were calculated as a function of the slope being simulated, using the equation: $f(\theta) = 0.65mg\sin\theta$.

### 2.2. New tilt mechanism

Originally, the Sarcos Treadport did not have a functioning tilt mechanism and experiments could only be done using the active tether. Prior to conducting this experiment, the Treadport was retrofitted with a hydraulic tilt actuator (fig. 2).

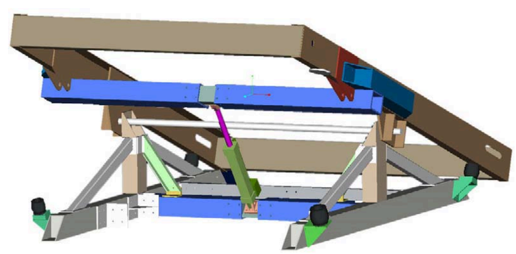


**Fig. 2.** Treadport frame with retrofitted hydraulic tilt actuator.

### 2.3. Metabolic measurements

Metabolic measurements were determined by measuring the volume of air inhaled (Hans Rudolph Pneumotach) and the percent of oxygen exhaled by a subject. The electronic oxygen analyzer (Ametek S3A-

I) was calibrated to the room air containing about 20.93% oxygen. $\dot{V}O_2$ was calculated based on the volume of air inhaled and percentage of oxygen consumed. The data were then adjusted to standard pressure. Two minutes of data were recorded and analyzed for each trial. Subjects were given three minutes to reach steady state prior to recording any data [3,8].

Different speeds were used during the experiment to help keep the subject in the center of the treadmill and to prevent the subject from going anaerobic (table 1). Normally, the walk/run gate transition occurs near 2.1 m/s, but for increased slopes this transition shifts to lower speeds [6]. However, when the subjects ran up the 12 degree slope at 1.6 m/s they had a modified running/jogging gate.

**Table 1.** Trial speeds [m/s]

| Angle | -15 | -12 | -9 | -6 | -3 | 0 |
|---|---|---|---|---|---|---|
| Walk | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1 |
| Run | N/A | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 |

| Angle | 3 | 6 | 9 | 12 | 15 |
|---|---|---|---|---|---|
| Walk | 1 | 1 | 1 | 0.8 | 0.8 |
| Run | 2.2 | 1.9 | 1.7 | 1.6 | N/A |

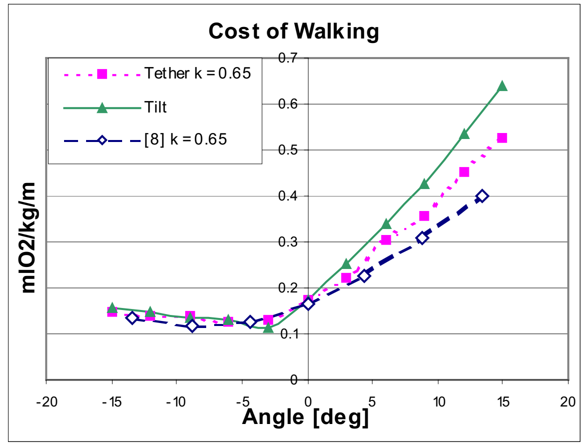
## 3. Results

The results for oxygen consumption ($\dot{V}O_2$) while walking and running on a slope were very similar to those previously published [2,7,13,14,15,17]. The energetic cost increased linearly as a function of positive slope and pulling (hindering) tether forces. For negative slopes and pushing (aiding) tether forces the energetic cost followed a curvilinear path with a minimum near negative six degrees. Figure 3 shows plots of the average oxygen consumption per angle of tilt for walking and running for all subjects. Oxygen consumption for the different tether forces is also plotted in figure 3 as a function of simulated tilt ($\theta_s$). Again, the tether force was equal to $f = Kmg\sin\theta_s$. For the experiments $K$ was assumed to be 0.65.

Data from [3,8] are also included in figure 3. The energetic cost for walking/running against a horizontal force was plotted as a function of simulated tilt using this equation:

$$\theta_s = \operatorname{asin}\left(\frac{\%bwt}{K}\right)$$

where %bwt is percent body weight force applied to subjects and $K$ can be varied to determine the best correlation to actual slope. When $K$ is equal to one, this



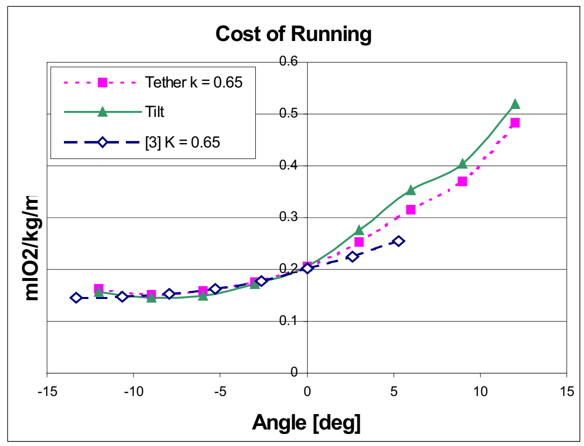




**Fig. 3.** Rate of $O_2$ consumed during walking and running with $K$ = 0.65. Cost of tether is significantly less for uphill slopes. Data from [3] and [8] are included for comparison and represent $O_2$ consumed during work against horizontal forces plotted as a simulated slope.

equation solves for the slope at which the %bwt force has the same magnitude as the component of gravity that must be overcome when going up or down that slope. For consistency, $K$ is again set equal to 0.65.

To compare the results of [3,8] with those in this paper, their data had to be normalized to account for any differences in velocity. This was accomplished by viewing the $\dot{V}O_2$ results on a cost per meter basis rather than a cost per minute. Some caution must be exercised when making this type of comparison. The energetic cost of walking is a function of speed and varies about ±15% between the speeds of 1.1 and 1.4m/s [16]. In [8] the speed was a constant 1.25 m/s.

This closely matches the speed of 1.3 m/s for the downhill portions of our experiments. However, the reduced speeds for the positive slopes in our experiment may account for some differences between the two results. Fortunately, the cost of running varies very little with speed [16, 6]. This is important because the running speeds are very different between [3], being 3.3 m/s, and our speeds being 2.2 m/s and even less for the more extreme positive slopes.

A least squares approach was used to determine the best values for $K$ to minimize the error between the tilt and tether energetic costs for each subject. The data were first divided between positive and negative slopes. Data from positive slopes were linearized. Data from negative slopes were fit to cubic polynomials to avoid symmetry. Matlab's nonlinear least squares routine was then run to determine the best values for $K$ to minimize the difference between the equations for tilt and tether. Each subjects' values for $K$ are shown in table 2. Subject six did not complete the running trials.

**Table 2.** LSQ Values for $K$

| | Walk | | Run | |
|---|---|---|---|---|
| Subject | Down | Up | Down | Up |
| 1 | 0.865 | 0.799 | 0.756 | 0.855 |
| 2 | 0.573 | 0.737 | 0.761 | 0.962 |
| 3 | 0.711 | 1.049 | 0.541 | 0.581 |
| 4 | 0.686 | 0.831 | 0.739 | 0.687 |
| 5 | 0.750 | 0.715 | 0.647 | 0.813 |
| 6 | 0.661 | 0.928 | -- | -- |
| 7 | 0.785 | 0.792 | 0.485 | 0.784 |
| Average | 0.719 | 0.836 | 0.655 | 0.780 |
| Std Dev | 0.0935 | 0.117 | 0.119 | 0.133 |

Figure 4 shows a plot of the average tilt and tether energetic costs using the new average values for $K$ for the positive slopes. The positive slope values for $K$ were selected because the energy cost between tilt and tether was significantly different for only the uphill slopes. This plot was created by viewing the previous tether forces as a function of percentage of body weight *(%bwt)*:

$$f = 0.65\sin(\theta)mg = (\%bwt)mg$$

and then relating the *%bwt* equation to the original equation:

$$f = K\sin(\theta_{adj})mg = (\%bwt)mg$$

$$\theta_{adj} = \operatorname{asin}\left(\frac{\%bwt}{K}\right) = \operatorname{asin}\left(\frac{0.65\sin(\theta_s)}{K}\right)$$

where $\theta_{adj}$ is the adjusted tilt angle that matches the real tilt for the given percent body weight force using the new average values for $K$.

In this way, the originally simulated tilt angle ($\theta_s$) of 15 degrees would match the energetic cost of walking up a real or adjusted slope of only 11.6 degrees ($\theta_{adj}$). This is the reason for increasing $K$ from 0.65 to 0.84 for walking uphill.

The adjusted plot for running shows less correlation for slopes above 9 degrees. This is most likely due to significantly reducing the speed for slopes above nine degrees to prevent the subjects from going anaerobic.

Running a statistical ANOVA on the data revealed a few points worth mentioning. First, a significant difference was found between the tilt and tether conditions for uphill slopes only. Second, for the walk uphill the difference between tilt and tether increased as a function of slope (see fig. 3). Third, the slope always had a significant effect on the energetic cost.

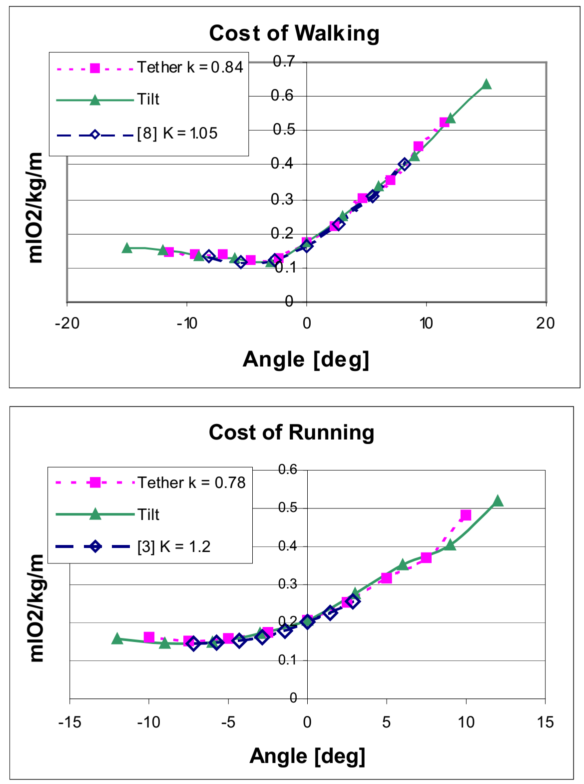



**Fig. 4.** Rate of $O_2$ consumed for walking and running using average values of $K$ = 0.84 and 0.78 derived to minimize the difference between tilt and tether for positive slopes. Data from [3,8] support values of $K$ greater than 1.0.

## 4. Discussion

The main purpose of this paper was to show that an active tether mechanism could realistically simulate the energetic cost of locomotion on different slopes. Such findings could be applied to virtual reality simulations using torso force feedback.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Now, after three different studies, $K$ has been found to be less than what was expected for each experiment. In theory, $K$ should be equal to one for simulating the component of gravity that must be overcome when traveling on a slope. However, psychological and biomechanical experiments supported an average value of 0.65 for $K$ and energetic experiments support values between 0.66 and 0.84. Why is $K$ less than one?

There are many reasons for which $K$ is less than one. Normally the gravity vector is distributed over the entire body. The tether represents a point-force application that is only partially distributed by the harness [9]. If the tether was attached below the subject's center of gravity the value of $K$ would perhaps increase because the effective moment arm between the point of force application and the subject's feet would have been shortened. Similarly, if the tether was attached above the subject's center of gravity there would perhaps be a need to reduce $K$ and apply less force to simulate an equivalent slope. One study was conducted on attaching the tether to the body at different heights [4]. It found that the amount a subject leaned was proportional to the tether's height above the hip. If we only desired to match how a subject leaned for real and simulated tilt it could be accomplished by changing the tether's force or the height of its attachment. In this experiment the subjects leaned in a similar manner for both real tilt and simulated tilt.

More work may be required of subjects if they do not lean enough to balance the torque applied by the tether about the ankle and feet. The tether force applies a torque to the body with a moment arm equal to the distance from the foot to the point of attachment on the body. To balance this torque, subjects must lean until their centers of mass are shifted enough over their feet to be equal and opposite to the applied torque from the tether. If subjects do not lean enough to balance the torque from the tether then the legs must supply the remaining torque. This remaining torque could add to the energetic cost for the simulated tilt condition. If the cost is higher than expected it gives one possible reason for $K$ to be less than one. Reducing the applied tether force reduces the overall energetic cost and makes up for the torque imbalance. This idea is only a theory and would require further investigation.

Researchers have also found that generating horizontal propulsive forces are almost four times more expensive than generating vertical forces while running on level ground [3]. This may be a result of the difference in the lengths of the moment arms over which these forces are applied. Assuming that the tether force requires the subject to exert greater horizontal forces also supports finding a value for $K$ to be less than one.

It must be noted that the data from [3,8] did not support a value of $K$ less than one. These data points show a good correlation to the energy cost of the actual tilt with $K$ values of 1.05 for walking and 1.2 for running (fig. 4). It is unknown as to why these values differed so much from those in this study. Many variables could affect the oxygen cost, but some of the main ones could be differences in: belt speeds, harness styles, harness positions, subject lean, and tether weight.

Another way to look at this data is to consider work efficiency. This topic is brought up in both [3,13]. The work efficiency is determined as:

$$\text{eff}_w = \frac{\text{external work rate}}{\begin{array}{c}\text{corresponding increase in metabolic rate}\\ \text{above the metabolic rate for zero load (level running)}\end{array}}$$

Work efficiency values from [3] ranged from 54.5% to 62.6% for negative forces. Our work efficiency values ranged from 33.1% to 42.7% for negative tether forces. Another study [12] supports our findings with average efficiencies ranging from 34.6% to 38.7% for horizontal work. (Note: an equivalent of 20.1 J/ml$O_2$ was used for conversion between ml$O_2$ and Joules [1].)

These horizontal work efficiency values can be compared to the efficiency for doing vertical work. In [3] they listed efficiencies for running up hills ranging from 45.6% to 46.6%. Our data shows efficiencies ranging from 36.5% to 46.1%. If it is more efficient to do horizontal work than vertical work it supports having values of $K$ greater than one. However, our data and those from [12] suggest that horizontal work is less efficient than vertical work and support a value of $K$ less than one.

It can be seen that $K$ varies slightly between walking and running. This must have something to do with the differences in gait between the two. One of the results from the ANOVA showed that for walking the difference between the tether and tilt increased as a function of simulated slope. Why did this only happen for walking and not for running? The answer may be in the differences between how the body supplies energy for walking and running. When walking, the ankle performs the majority of positive work (53%), then the hip (43%), and finally the knee (4%). When running, the demand on the ankle is reduced to 41%, then the hip (37%), and the knee (22%) [16]. The horizontal tether force may have a greater effect on walking because the ankle is doing more work. As the speed increases to a run the more proximal joints provide the majority of energy [16]. The tether force may not have as much of an effect on the proximal joints because of their shorter moment arms. Overall, the differences in $K$ between walking and running were not statistically significant.

Presently, when running the virtual reality simulation, both the actual tilt and simulated tilt (tether force) are combined. When the subject is traveling through the virtual world and comes to a change in slope the tether quickly applies the appropriate force to simulate the slope. The deck also starts to tilt at a rate of 5 degrees per second. This rate was determined based on the subjects' comfort and safety. As the deck tilts the tether force is reduced until the slope is rendered using half of the tether and half of the actual slope. By dividing the slope display evenly between the tether and tilt it doubles the amount of slope that can be rendered on the Treadport. The deck is only physically able to tilt 20 degrees, but with the addition of the tether force the Treadport can render nearly a 40 degree slope.

In conclusion, an applied horizontal tether force can successfully match the energetic cost of locomotion on a slope. Different values of $K$ in $f = Kmgsin(\theta)$ may be used to best match the actual slope $\theta$ for positive and negative slopes. Average values of $K$ ranged from 0.66 to 0.84 for walking and running on positive and negative slopes. These numbers reaffirm the support for a value of $K$ that is less than one.

## 5. Acknowledgements

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