The Biomechanical Fidelity of Slope Simulation on the Sarcos Treadport Using Whole-Body Force Feedback

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Abstract: This paper addresses whether whole-body force feedback on treadmill-style locomotion interfaces can simulate the gravity forces experienced when walking on smooth inclines. By applying horizontal force feedback possible with the active mechanical tether of the Sarcos Treadport, it is shown that the biomechanics of walking are similar under conditions of real slope walking versus tether force walking. These biomechanical results complement previous psychophysical studies which yielded the same result, to conclude definitively that whole-body force feedback can realistically substitute for treadmill tilt.

1. Introduction

This paper addresses the issue of how well walking on sloped surfaces can be simulated on a locomotion interface using whole-body force feedback instead of actually tilting the walking surface. The Sarcos Treadport uses an active tether mechanism which both senses user position and applies forces to the user (Figure 1). This tether attaches to the user's back via a whole-body harness, and can apply a force along its linear axis. The tether can be used to simulate the extra gravity forces in slope walking by pulling or pushing on the user in the direction of walking. Because of its higher bandwidth, tether force can represent fast slope transients and is potentially a replacement for having a tilt mechanism at all. This has the added advantage of simplifying video displays which use mechanisms such as back-projected screens. Whole-body force feedback has other important uses as well, such as simulating hitting a wall or inertial forces during running [1].

When walking on a real slope, the gravity force f parallel to the slope that retards or assists walking is $f = mg\sin\theta$, where m is the user's mass, $g = 9.8m/s^2$ is gravity, and θ is the slope (Figure 2(A)). This gravity force can instead be applied by the mechanical tether to simulate slope walking (Figure

Figure 1. The Sarcos Treadport with tether attachment to a user.

2(B)).

Previously we reported psychophysical results on the subjective equivalence of tether force for slope walking [7]. We asked subjects to walk on a tilted treadmill, then to walk on a flat treadmill but to adjust the tether force until it felt most like walking on the reference slope. We obtained a linear relationship between preferred tether force and slope, indicating psychological equivalence.

$$f = 0.65 m g \sin\theta \tag{1}$$

The fractional force preference of 65% was hypothesized to arise either from localized force application to the body through the harness or through a simplified mechanical model of the human as a lumped mass m. A similar fractional force preference was also found for inertial force display [1].

A more quantitative test would be to show biomechanical equivalence, i.e., the gait patterns are the same for the two situations. It is not unreasonable to expect a biomechanical correlate because a user has to lean against the tether force, in a manner which could conceivably be similar to leaning while walking on a slope. This paper presents such a biomechanical analysis.

Past research on the biomechanics of slope walking have employed various kinematic measures to quantify the change of gait with slope, such as leg joint angle ranges [4] and the knee-hip cyclogram [2]. We have examined a range of measures to deduce what is the best biomechanical correlate for slope, then used such a measure to show that the biomechanics of slope walking versus tether force walking are indeed similar.

2. Methods

Measurement of gait was done with the Northern Digital Optotrak System, which involves placement of active LED markers on the foot, calf, thigh, and hip (Figure 3). Special rigid bars for LED mounting were created to facilitate

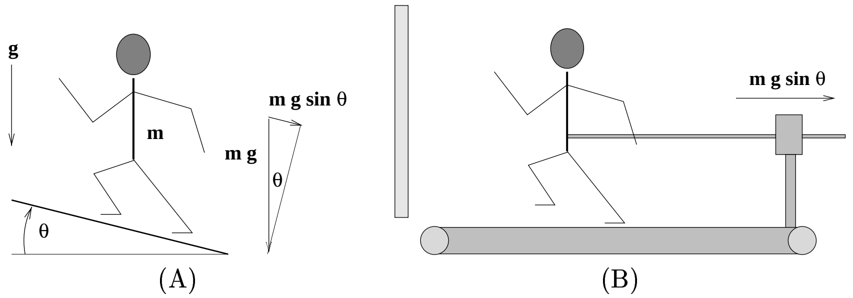

Figure 2. (A) Gravity force $mg \sin\theta$ opposes uphill walking. (B) Simulation of this gravity force with an active mechanical tether.

joint angle calculation by considering these bars as vectors representing absolute orientation of leg segments. Padding and straps were employed to ensure tight but comfortable coupling to the limbs.

Two different generations of Treadport were employed in this study. The second-generation Treadport has a redesigned belt drive and mechanical tether which are improvements over the first-generation Treadport [3], but does not yet have a functioning tilt mechanism. Therefore we employed the first-generation Treadport to generate a tilted walking surface and the second-generation Treadport to apply tether forces.

The gaits of six subjects, three male and three female, were measured both while walking on a tilted belt and while walking on a flat belt but with tether force application. The tether force is applied to a user via a whole-body harness to which the active mechanical tether attaches. The tether utilizes a linear drive consisting of a timing belt and geared electric motor [3], and is capable of exerting 315 N.

For the treadmill tilt experiments, the subject walked on the first-generation Treadport and the slope of the Treadport was varied randomly at two degree intervals between 6 degrees downhill and 14 degrees uphill. This range was dictated by the asymmetry of the tilting mechanism of the first-generation Treadport. For the tether force experiments, the subject walked on the second-generation Treadport and forces on the tether were varied randomly from -100 N to 45 N, depending on the subject's mass. A negative force corresponds to a force pulling the subject and therefore simulates a positive slope, and a positive force simulates a negative slope accordingly. Both Treadports were kept at a constant walking speed throughout the experiment.

3. Results

The data collected is similar across all of the subjects. Hence we present representative results of one specific subject (a female) to show the trends and characteristics that are common to all subjects in the experiment. Knee and hip angles were derived from the positions of the sensors and then plotted against one another. These plots are the knee-hip cyclograms found in Figures 4 and 5. Figure 4 shows how cyclograms change according to variation

Figure 3. Marker attachment for leg joint angle measurements.

in slope. As the slope increases, the cusp of the cyclogram rotates clockwise, the knee and hip angle ranges widen, and the overall shape of the cyclogram becomes more oblong. The cusp happens at footfall, where the knee flexes almost elastically before straightening out to push off.

Figure 5 shows how the cyclograms change according to various tether forces applied to the subject. The cyclogram trends are similar to those of Figure 4; the cusp rotates clockwise, knee and hip angle ranges widen, and the overall shape of the cyclogram becomes more oblong.

These visual changes and trends can be captured quantitatively using moment-based analysis of the cyclograms and by joint angle ranges. Using this analysis the following statistics were calculated: hip range, knee range, ratio of hip range/knee range, ratio of knee range/hip range, area of cyclogram, circularity, eccentricity, orientation, and cusp orientation. These values are shown in Figures 6 and 7. Once again the general trends of the cyclogram are similar as the slope and tether force change from smaller slopes to larger slopes.

To find a relationship between tether force and the simulated slope angle, least squares equations were found for each of the properties of the cyclogram for all subjects. The most linear properties across both slope and force were the hip range, the knee/hip range ratio, the cyclogram orientation, and the cyclogram cusp orientation. Analysis of variance accounted for (VAF) for all subjects showed that hip range is consistently the most linear feature with slope or force, and hence is used in the subsequent analysis. Straight line fits were made to hip range versus force $HR = af + b$ and hip range versus slope $HR = c\theta + d$ for each subject. The approximation $\theta \approx \sin\theta$ is used, which only

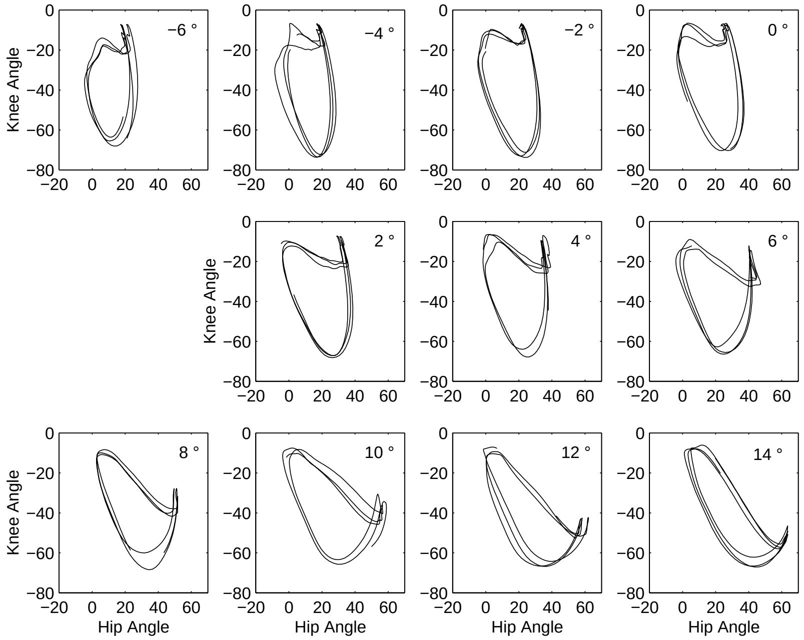

Figure 4. Hip-knee cyclograms at different slopes.

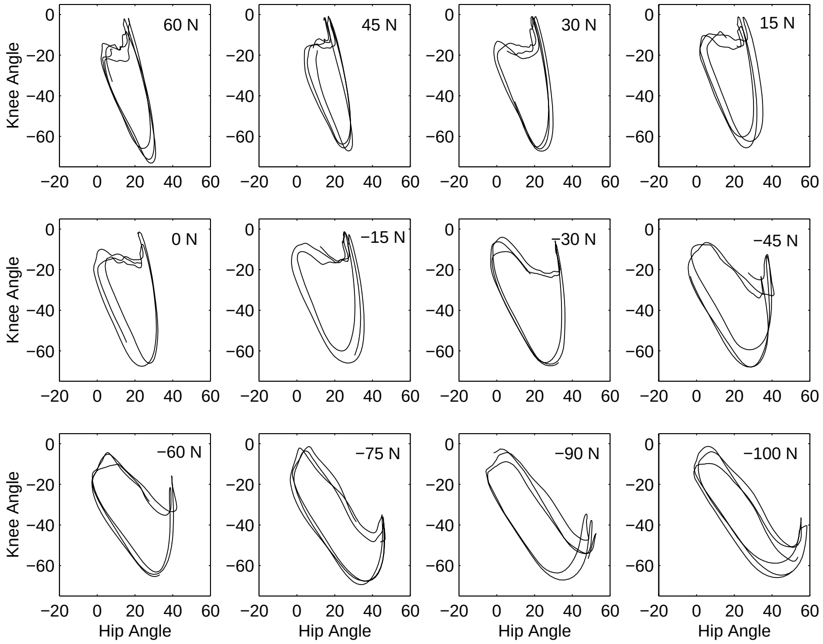

Figure 5. Hip-knee cyclograms at different tether forces.

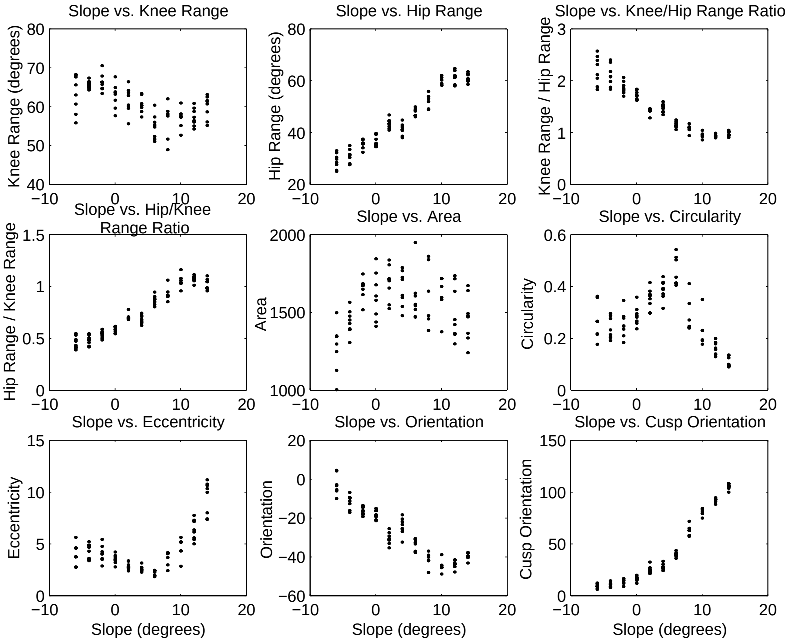

Figure 6. Properties of cyclograms as they change according to slope.

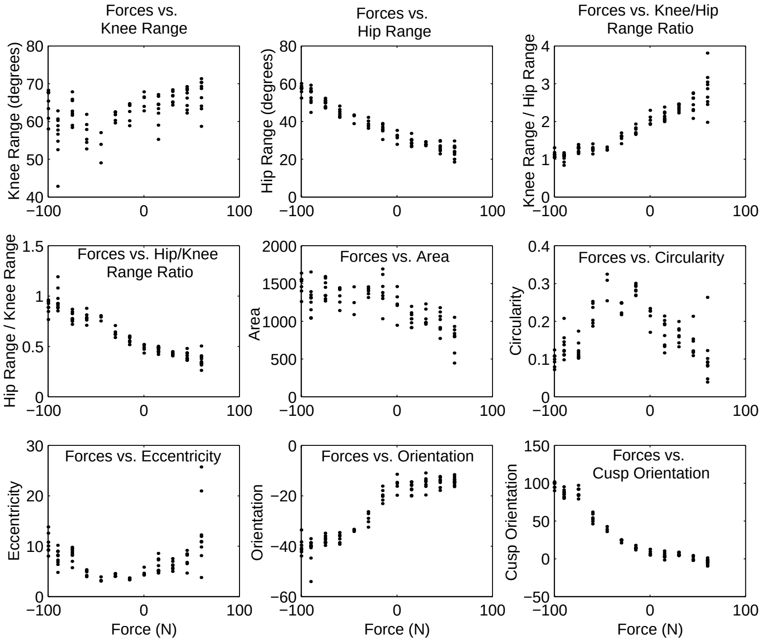

Figure 7. Properties of cyclograms as they change according to tether force.

Subject	c/a	$(d-b)/a$	$c/a/mg$
1	-437	2.0	0.647
2	-289	-15.5	0.520
3	-494	-19.8	0.756
4	-444	-17.9	0.526
5	-576	32.0	0.730
6	-480	3.6	0.663

Table 1. The slope c/a and intercept $(d-b)/a$ of the experimentally derived linear relation between tether force and slope, and the fractional force result $c/a/mg$.

has a 1% error at the maximum tilt of 14 degrees. Then a relation between the tether force and slope could be predicted as:

$$f = \frac{c}{a}\theta + \frac{d-b}{a} \tag{2}$$

Table 1 shows the results for the six subjects. We are expecting a relation $f = mg \sin\theta$, so the intercept $(d-b)/a$ not being zero is an indication of the approximation of the linear fits.

As mentioned earlier, it was found from psychophysical experiments that there was a fractional force preference of 65% of the full predicted gravity force, i.e., $f = 0.65mg\sin\theta$ [7]. Dividing the slope c/a by a subject's weight mg indicates what would be any fractional force determined from biomechanics. The last column in Table 1 shows these fractional forces, which range from 52% to 73%. These results are in the vicinity of the average result 65% found from the psychophysical studies of [7].

4. Discussion

These results demonstrate that the horizontal tether force changes a person's gait in a manner that is similar to the gait changes of the person walking on different slopes. This means that an applied force from the tether is biomechanically a reasonable simulation of inclined surfaces. These results complement the previously reported psychophysical results which showed the same result [7]. In combination, the biomechanical and psychophysical results demonstrate conclusively that tether force can reasonably simulate walking on slopes.

There is an implication for treadmill design, because one can now choose between treadmill tilt and tether force to simulate slope. There are already reasons to include an active mechanical tether with treadmills when creating locomotion interfaces, such as inertial force display [1], the display of hitting objects, safety restrictions to range of forward motion on the treadmill surface, and accurate tracking of user position. One can then add to that list the accurate display of slope.

Although treadmill tilt of course displays slope realistically, there are some reasons against tilt implementations. The treadmill surfaces are large and heavy, especially the large 6-by-10 foot surface of the Sarcos Treadport II, and so the tilt mechanism adds cost and complexity to the design and will be slower than the fast-acting mechanical tether. When using a stationary CAVE visual display, a tilted platform would obscure portions of the screens. An alternative is to mount the CAVE on the treadmill (Noma, personal communication), although the size of the display will be necessarily limited. If projection onto the belt surface is contemplated, then the image will be distorted and will have to be compensated for by computation.

Several gait features were found to have approximately linear relationships with slope or tether force: hip range, the knee/hip range ratio, the knee/hip cyclogram orientation, and the knee/hip cyclogram cusp orientation. Of these the hip range was the more linear. Hip range was also noted as an important slope indicator by [4], although the plots of hip range versus slope were not as linear as what we found. Goswami had previously characterized higher-order moments of the knee/hip cyclograms as good descriptors of slope walking [2]. Our work has shown that the orientation of the knee/hip cyclogram as a whole and the orientation of just the cusp part of the knee/hip cyclogram provided good linear characterizations of slope walking.

The good linear fits of tether force to hip range and treadmill tilt to hip range allowed a prediction of tether force to treadmill tilt. By dividing the slope of the linear relation of tether force to treadmill tilt angle by each subject's weight, it was found that a fractional application of force between 52% and 73% of the expected amplitude $f = mg \sin\theta$ was appropriate to represent a particular slope θ. This result is consistent with the 65% fractional preference determined from psychophysical experiments [7]. Because the fractional forces were derived from biomechanics, it must indeed be the case that the proper tether force is not 100% of the predicted gravity force $f = mg \sin\theta$. As mentioned earlier, the cause of the fractional force must have something to do with the point-force application to the body by the tether or by the method of force distribution to the body by the harness. An exact explanation for the fractional force based on a mechanical analysis awaits future analysis.

An application of these results besides virtual reality is in the use of treadmills for legged robot research. For example, treadmills have been built for the running robots of [6] and [5]. Our results suggest that slopes could be simulated for the running robots by adding an active mechanical tether. In addition, the mechanical tether could supply realistic inertial forces to those robots [1].

Acknowledgments

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References

[1] Christensen RR, Hollerbach JM, Xu Y, Meek SG 2000 Inertial-force feedback for the Treadport locomotion interface. *Presence: Teleoperators and Virtual Environments.* 9:1-14.

[2] Goswami A 1998 A new gait paramterization technique by means of cyclogram moments: application to human slope walking. *Gait & Posture.* 8(1):15-36.

[3] Hollerbach JM, Xu Y, Christensen R, Jacobsen, SC 2000 Design specifications for the second generation Sarcos Treadport locomotion interface. *Haptics Symposium, Proc. ASME Dynamic Systems and Control Division, DSC-Vol. 69-2,* Orlando, Nov. 5-10, 2000, pp 1293-1298.

[4] Masmoudi L-A, Martin L, Cordier E, Blanchi, J-P 1999 Kinematics analysis of human slope walking. *1st Intl. Conf. on Science & Technology in Climbing and Mountaineering.* Leeds.

[5] Moghaddam M, Buehler M 1993 Control of virtual motion systems. *Proc. IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems,* Yokohama, July 26-30, pp 63-67.

[6] Raibert MH 1986 *Legged Robots That Balance.* MIT Press, Cambridge, MA.

[7] Tristano D, Hollerbach JM, Christensen R 2000 Slope display on a locomotion interface. In: Corke P, Trevelyan J (eds) *Experimental Robotics VI,* Springer-Verlag London, pp 193-201.