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Abstract
In a recent paper [1] Borghese *et al.*, demonstrated that 4D pelvis-thigh-shank-foot cyclograms of human locomotion are surprisingly planar, if the segmental elevation angles rather than the traditional inter-segmental angles are used. In this work, we demonstrate that the planarity of elevation angle cyclograms is preserved even for slope walking, within a 15 degree range.

Comments
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CYCLOGRAM PLANARITY IS PRESERVED IN UPWARD SLOPE WALKING

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Motivation

In a recent paper [1] Borghese et al. demonstrated that 4D pelvis-thigh-shank-foot cyclograms of human locomotion are surprisingly planar, if the segmental elevation angles rather than the traditional inter-segmental angles are used. In this work, we demonstrate that the planarity of elevation angle cyclograms is preserved even for slope walking, within a 15 degree range.

Methods

Three healthy adult volunteers (1 female, 2 male, ages 20-36) participated in this study after giving informed consent. The subjects were asked to walk at freely chosen speeds on three surface inclinations: 0 degrees, 8 degrees, and 15degrees. Each subject performed 20 trials on each slope angle. A variable inclination ramp (366 cm L x 60 cm W) was constructed for this purpose.

We used a single camera system from Vision 1 Corp. to record sagittal plane position data at 30 Hz for five reflective markers attached to bony landmarks [1]: anterior superior iliac crest, greater trochanter, lateral femur epicondyle, lateral malleolus, and fifth metatarsophalangeal joint. At each time instant, the elevation angles of the thigh, shank, and foot were extracted from the marker positions and plotted in a 3 dimensional space. Over a complete gait cycle, these points form a curve - the cyclogram. Pelvis elevation angles were also extracted but were ignored here for 3D illustration purposes. However, the results hold when the pelvis elevation angles are included.

To determine the best-fit plane of the cyclogram, we first translate all the points so that they are centered around the origin. We then calculate the eigenvalues and eigenvectors of the covariance matrix of the points. The eigenvectors corresponding to the two larger eigenvalues lie in the best-fit plane and the third eigenvector is normal to the plane [1]. Using the third eigenvector and the origin as a point on the plane, we compute each point's distance from the plane.

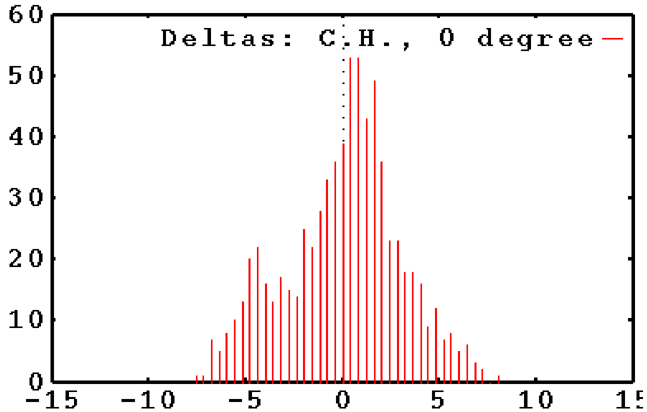
Results

The ratio of the smallest variance to the total variance is the amount of variation not accounted for by the eigenvectors in the plane [1], the off-plane variance. A smaller ratio indicates a better planar fit.

Subject	0 degree slope	8 degree slope	15 degree slope

C.H.	.440%	.621%	.821%
S.W.	.567%	.627%	.833%
S.P.	.853%	1.147%	1.022%

Table 1: Percent of variance not accounted for by eigenvectors in the plane



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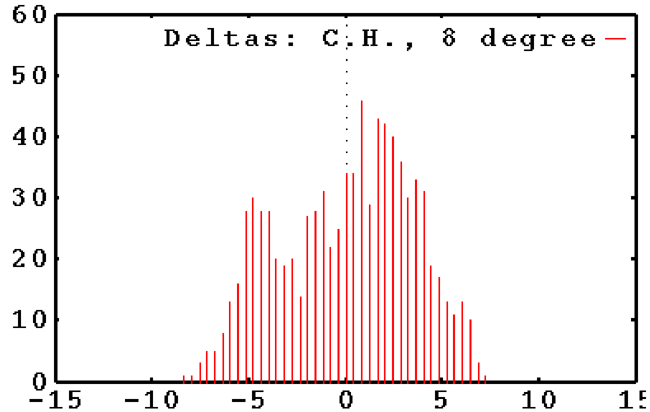

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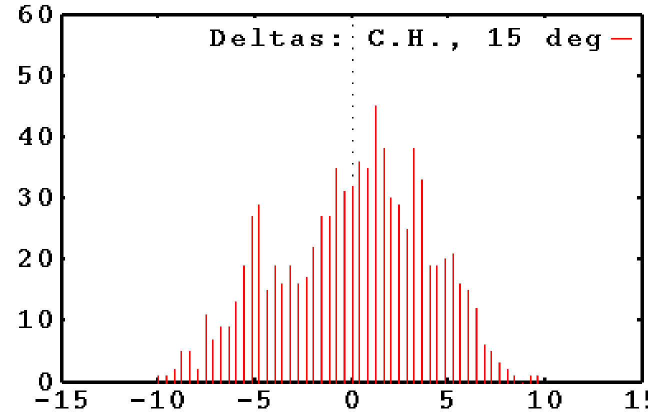

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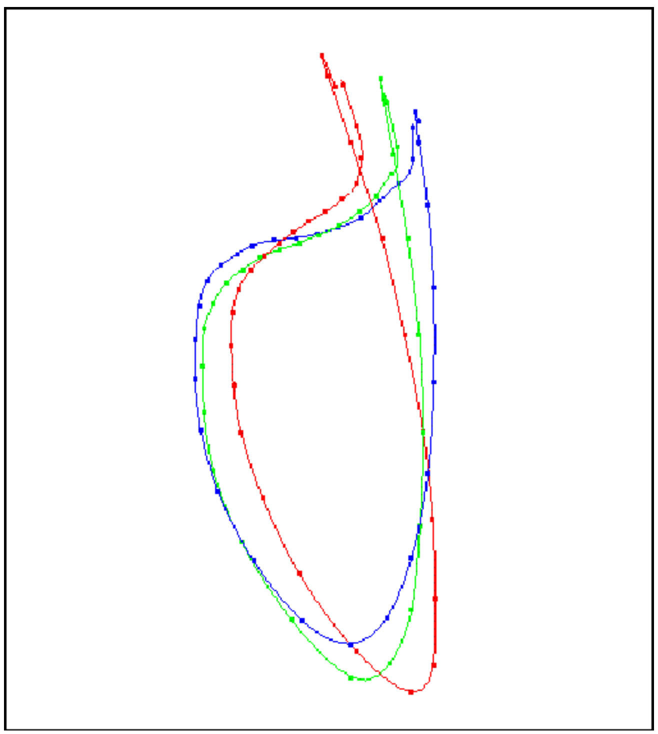

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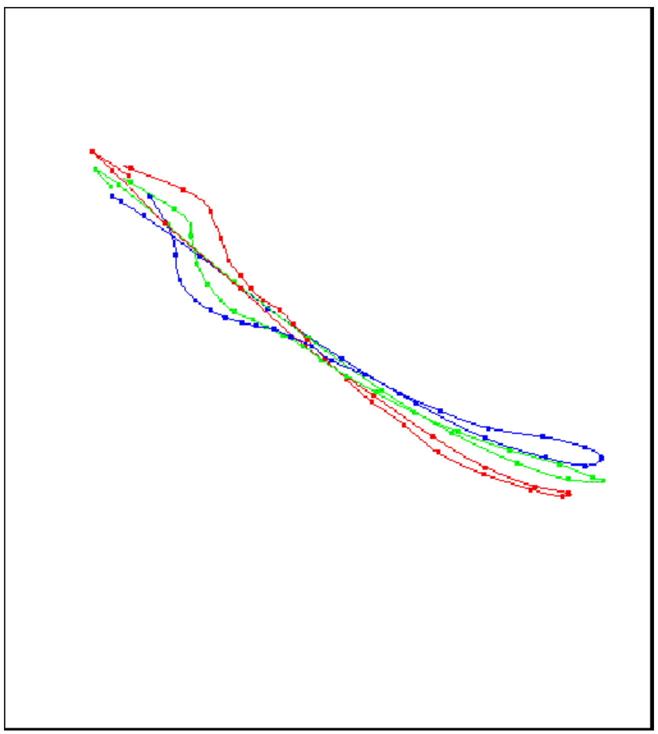

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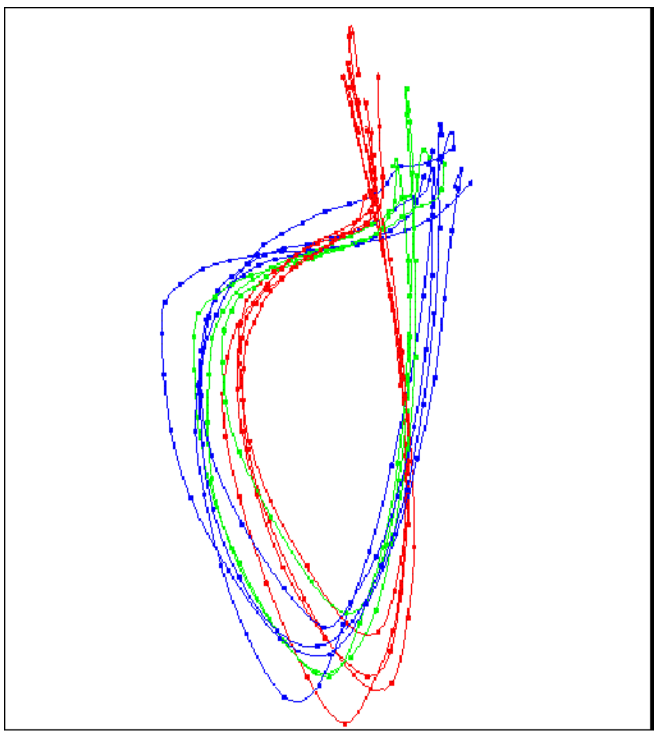

(f)

Figure 1: (a-c) Histograms of the distances between cyclogram points and the best-fit plane: (a) 0 degrees (b) 8 degrees (c) 15 degrees
(d-e) Cyclogram from one subject (d) normal projection (e) side projection. (f) Cyclograms from all subjects (normal projection). Red = 0 degrees, blue = 8 degrees, green = 15 degrees

While the off-plane variance increases with the slope angle, the amount of increase between 0 degree and 8 degree is small (.381% maximum). Figure 1 shows the histograms of the distance between the cyclogram points and the best-fit plane for subject C.H. Note that the distributions are unimodal but the standard deviation increases with the slope angle. In Figure 1(e), the plane of the elevation angles can be seen to rotate as slope angle increases, while the curve rotates in the plane as well (Figure 1(d)(f)).}

Bibliography

A. Borghese, L. Bianchi and F. Lacquaniti. Kinematic determinants of human locomotion. *J. Physiology*, 494:863-879, 1996.