LONG-RANGE CORRELATION IN HUMAN JOINT-ANGLE VARIABILITY DURING WALKING

Dorothea J. Tsang, Meghan E. Lukac, and Anne E. Martin
Pennsylvania State University
Email: djt5071@psu.edu, mpl5351@psu.edu, aem34@psu.edu

INTRODUCTION

Human walking exhibits long-range correlation between stride durations [1]. These correlations measure how variation in one step influences variation in later steps. For example, a quick step will tend to be followed by more quick steps if the gait has a long-range correlation. These correlations are altered with age and some diseases and may provide information about walking ability [1]. The variability in stride durations occurs at least in part due to variation in joint angles [2]. It is not clear, however, if the joint angle variability also exhibits long range correlations given that these correlations can arise from the controller [3] or the natural dynamics of the system [4]. This study begins to quantify the long-range correlations in the joint angles during healthy human walking.

METHODS

Two healthy young adult females walked on a treadmill (Bertec, Columbus, OH) for ten minutes at an average speed of 1 m/s while kinematic data were collected at 100 Hz (Vicon, Oxford, UK). Prior to the experiment, each subject chose a comfortable speed. All data was processed using Nexus (Vicon, Oxford, UK) with the plug-in gait model and standard filtering parameters. For gaps of less than 20 frames, the cyclic method was used to fill the gap, while the spline method was used to fill longer gaps. Data was divided into stance and swing periods, and the periods were analyzed separately. The left and right legs were also analyzed separately. For each joint, the per-subject mean angle was subtracted from the total angle for each step to obtain the joint variability. To parameterize the variability mathematically, a second- (stance) or first- (swing) order Fourier series was fit to the variability [2]:

$$q_{vij}(t) = a_{0ij} + a_{1ij}\cos\omega_{ij}t + b_{1ij}\sin\omega_{ij}t + a_{2ij}\cos 2\omega_{ij}t + b_{2ij}\sin 2\omega_{ij}t$$

where q_{vji} is joint j's variability for step i. For each step, the Fourier series is described by frequency (ω_{ij}) and magnitude (a_{0ij}, a_{1ij}, b_{1ij}, a_{2ij}, b_{2ij} where $a_{2ij} = b_{2ij} = 0$ for the swing joints) coefficients. Long-term correlations in frequency indicates that the timing of the variability is correlated while correlations in the magnitude coefficients indicates that size of the variability is correlated. To quantify the long-term correlations, detrended fluctuation analysis was performed [5] using 19 sample sizes ranging from 4 to 128 steps. For each sample size, data was divided into equal, non-overlapping segments, and the local root-mean-square (RMS) was computed. The slope of the linear regression line of the average RMS versus the segment sample sizes in log-coordinates is the Hurst exponent. A Hurst exponent of 0.5 indicates white noise and no long-term correlations. A Hurst exponent of > 0.5 indicates long-term correlations. The Hurst exponent for each frequency and magnitude coefficient was calculated separately. The Hurst exponent for stride duration was also found.

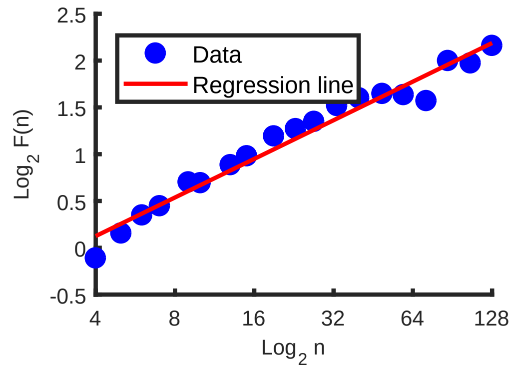

Figure 1: Average RMS vs. segment sample size in log-coordinates for the right stance hip frequencies of subject 1. The data is well fit by a line. The Hurst exponent is 0.41, indicating no long-range correlations.

RESULTS AND DISCUSSION

The subjects took 503 and 549 strides respectively. For scales of 4 to 128 steps, linear regression lines well fit the average RMS with R^2 values consistently ≥ 0.97 (Fig. 1). A scale exceeding 128 steps resulted

Table 1: Hurst exponents for the joint angle magnitude and frequency coefficients. The range of values for each coefficient is given. The data appears random with no long-term correlations regardless of period and joint.

	$\mathbf{a_0}$	$\mathbf{a_1}$	$\mathbf{b_1}$	$\mathbf{a_2}$	$\mathbf{b_2}$	ω
Stance Hip	0.53 - 0.59	0.50 - 0.58	0.46 - 0.53	0.50 - 0.60	0.48 - 0.56	0.41 - 0.50
Swing Hip	0.54 - 0.59	0.52 - 0.55	0.57 - 0.66	-	-	0.52 - 0.54
Stance Knee	0.51 - 0.64	0.51 - 0.62	0.52 - 0.58	0.56 - 0.61	0.55 - 0.64	0.48 - 0.58
Swing Knee	0.52 - 0.59	0.51 - 0.60	0.52 - 0.63	-	-	0.48 - 0.54
Stance Ankle	0.46 - 0.55	0.52 - 0.58	0.44 - 0.55	0.47 - 0.55	0.48 - 0.61	0.47 - 0.54
Swing Ankle	0.48 - 0.58	0.45 - 0.55	0.51 - 0.65	-	-	0.50 - 0.64

in RMS points that deviated from the trend apparent at smaller scale segments, suggesting insufficient data for the larger scales. There are clear long-term fluctuations in stride duration (Fig. 2). The average Hurst exponent was 0.75 which aligns closely to values reported in literature [6]. In contrast, the joint variability magnitude and frequency coefficients do not appear to exhibit long-range correlations (Fig. 2). This is confirmed with Hurst exponents ranging from 0.41 to 0.66 (Table 1). In all cases, both subjects and the left and right sides had similar values. The average Hurst exponent for the frequency coefficients over all joints and periods and for both subjects is 0.52. The average Hurst exponent for the magnitude coefficients over all joints and periods and for both subjects are 0.55 for a_0, 0.55 for a_1 and b_1, and 0.53 for a_2 and b_2. Since the Hurst exponents are all approximately 0.5, this indicates that joint variability may just be white noise. These results agree with the observation that long-term fluctuations in step duration occur with white noise in a push-off force [4].

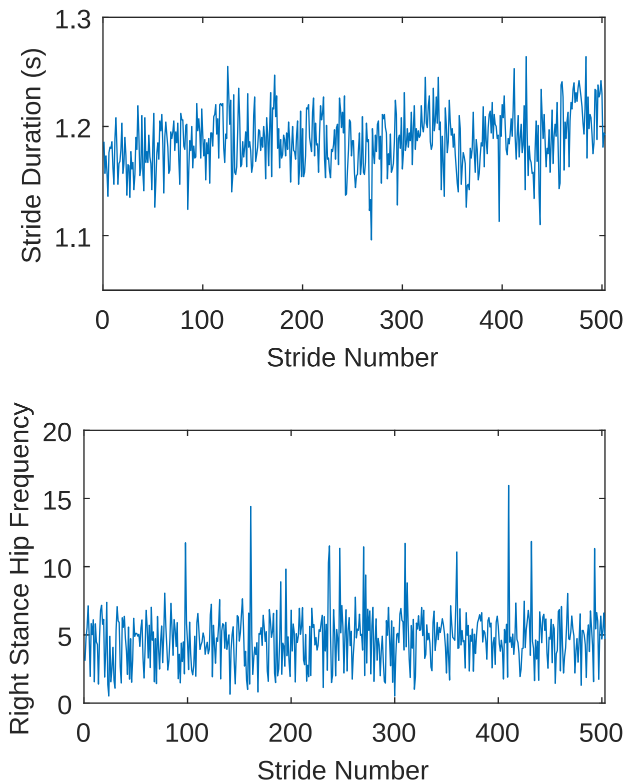

Figure 2: Stride duration (top) and right stance hip frequencies (bottom) vs. stride number for subject 1. The stride durations exhibits long-term correlations while the frequencies are random with no long-term correlations. The plots for the other frequencies and magnitudes coefficients for both subjects are similar.

CONCLUSIONS

In contrast to the stride duration variability, the joint angle variability does not appear to exhibit long-range correlations. Instead, it has an anti-correlated, time-independent structure, at least when each coefficient is analyzed independently. This suggests that the long-term correlations in stride duration may arise from the natural dynamics of the system rather than from correlations in the leg kinematics.

REFERENCES

[1] Hausdorff, JM. *Hum Movement Sci* **26**, 555–589, 2007.
[2] Martin, AE, et al. *J Biomech* **49**, 3298–3305, 2016.
[3] Dingwell, JB & Cusumano, JP. *PLOS ONE* **10**, e0124879, 2015.
[4] Ahn, J & Hogan, N. *PLOS ONE* **8**, e73239, 2013.
[5] Ihlen, EAF. *Front Physiol* **3**, 141, 2012.
[6] Rhea, CK, et al. *Hum Movement Sci* **36**, 20–34, 2014.