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ScienceDirect

Gait & Posture 26 (2007) 128–134

GAIT & POSTURE

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Walking speed influences on gait cycle variability

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Received 23 May 2006; received in revised form 9 August 2006; accepted 14 August 2006

Abstract

The purpose of this study was to investigate the influence of walking speed on the amount and structure of the stride-to-stride fluctuations of the gait cycle. Based on previous findings for both walking [Hausdorff JM, Purdon PL, Peng CK, Ladin Z, Wei JY, Goldberger AL. Fractal dynamics of human gait: stability of long-range correlations in stride interval fluctuations. J Appl Physiol 1996;80:1448–57], and running [Jordan K, Challis JH, Newell KM. Long range correlations in the stride interval of running. Gait Posture 2006;24:120–5] it was hypothesized that the fractal nature of human locomotion is a reflection of the attractor dynamics of human locomotion. Female participants walked for 12 min trials at 80%, 90%, 100%, 110% and 120% of their preferred walking speed. Eight gait cycle variables were investigated: stride interval and length, step interval and length, and from the vertical ground reaction force profile the impulse, first and second peak forces, and the trough force. Detrended fluctuation analysis (DFA) revealed the presence of long range correlations in all gait cycle variables investigated. Speed related U-shaped functions occurred in five of the eight variables, with the minima of these curves falling between 100% and 110% of the preferred walking speed. These findings are consistent with those previously shown in running studies and support the hypothesis that reduced strength of long range correlations at preferred locomotion speeds is reflective of enhanced stability and adaptability at these speeds.

Keywords: Walking; Variability; DFA; Stability

1. Introduction

Walking is one of the most practiced of all motor skills, thus, it is not surprising that there is a very low level of variability (e.g. coefficient of variation $\approx 3\%$) associated with many biomechanical measures of this task, e.g. [1,3]. This low level of variability is generally taken to mean that a very repeatable movement pattern has been attained [3]. Traditionally this variability has been regarded as a (white) noise process, where any given fluctuation in the time series is independent of all other fluctuations. However, in the last decade it has become apparent that in both walking [1,4] and running [2], that stride-to-stride fluctuations (i.e. stride interval variability) contain structure in the form of long range correlations. Statistically, this means that the stride interval at any point in the time series is related to or dependent upon the stride interval at remote previous times.

This type of long range dependence is common in physiological time series and has been used as an indicator of overall adaptability of particular systems. For example, the fluctuations of a healthy heart show complex multi-scale long range order, whereas heart disease results in a change in the scaling behavior such that the fluctuations are limited to either very few time scales (excessive predictability) or uncorrelated randomness (e.g. [5]). Similarly, it has been shown that the scaling behavior of the stride interval of human walking becomes more random-like with aging and disease [6]. One finding of relevance here is that the strength of the long range correlations of healthy young adults in both gaits appears to be speed dependent [1,2], but there has been no systematic investigation of the speed-long range correlation function in walking.

Studies investigating variability of the step interval and length have revealed U-shaped patterns of change with speed

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0966-6362/$ – see front matter
doi:10.1016/j.gaitpost.2006.08.010

for the coefficient of variation (CV) of both of these variables [7,8]. It is also known that individuals exhibit a preference for a particular walking speed, which occurs at or close to the speed at which energy consumption (per unit distance) is minimized [9]. Results from both walking [10], and leg swinging [11] studies provide evidence that the metabolic cost of walking is minimized by taking advantage of the passive mechanical properties of the leg, which in turn reduces the required force contribution of muscle. When walking at a constant speed, preferred and predicted periods of oscillation are not significantly different, and these periods coincide with minimum metabolic expenditure [12]. Collectively, these findings support the idea of a preferred walking speed (PWS) which is related to the mechanical properties of the leg.

Within the dynamical systems motor control framework, the preferred parameterization of movement patterns (in this case PWS) is associated with the concept of an attractor [13]. An attractor can be regarded as a pattern of behavior towards which a system is drawn [14]. Preferred behavior of a system is regarded within this framework as being close to an attractor and hence stable. As the behavior of the system moves away from the attractor (for example by increasing or decreasing walking speed) it is expected that there will be a loss of stability. It follows from the results of Holt and coworkers [10,12] that the preferred walking speed, related as it is to the eigenfrequency of the limb, is the most stable in terms of the attractor dynamics of the system. Here we examine the proposition that the apparent reduction in long range correlations at the preferred walking speed may be related to the attractor dynamics of walking.

The purpose of the current study was to investigate the influence of walking speed on the amount and structure of the stride-to-stride fluctuations of the gait cycle. Based on previous findings for both walking [1] and running [2], it was hypothesized that long range correlations would be present in gait cycle variables other than stride interval, that the effects of speed would be similar across these variables, and, that the preferred walking speed would be that at which the long range correlations were the weakest.

2. Methods

2.1. Subjects

Eleven female volunteers from The Pennsylvania State University between the ages of 22 and 30 years of age (average age = 24.9 ± 2.4 years; average height = 164.9 ± 5.1 cm; average mass = 57.2 ± 3.1 kg) were recruited for the study. All participants were healthy non-smokers with no history of cardiovascular disorders and were required to fill out a physical fitness readiness questionnaire (PAR-Q) to ensure they were suitable candidates for an exercise test. Additionally, in order to minimize fatigue effects, participants were well trained recreational runners who ran for a minimum of 15 miles per week. All participants provided informed consent and all procedures were approved by the Institutional Review Board of The Pennsylvania State University.

2.2. Apparatus

The apparatus consisted of a Kistler Gaitway treadmill with two embedded force plates. Vertical ground reaction forces (VGRF) were measured by uni-dimensional piezo-electric force sensors and sampled at a rate of 250 Hz. The treadmill had a speed range of 0.8–20 km/h, the smallest increment in speed was 0.1 km/h.

2.3. Tasks and procedures

On a day prior to data collection participants spent 45 min walking on the treadmill at speeds at which they felt comfortable, to become familiar with the treadmill. The first 10 min of each experimental session was used as a warm up/treadmill adaptation period, participants were prevented from viewing the speed at which they were walking. The PWS was established during this period by initially having the participant walk at a relatively slow speed, the investigator then increased the speed in 0.1 km/h increments until the subject reported that they were walking at their PWS. The speed was then increased by approximately 1.5 km/h and then decremented by 0.1 km/h until the PWS was re-established. This procedure was repeated until a close match was achieved (less than 0.4 km/h different)—in the majority of participants a similar speed was arrived at on the first two attempts to establish PWS.

Participants performed one 12 min trial at each of the following percentages of preferred walking speed: 80%, 90%, 100%, 110% and 120%. Speeds were presented randomly and participants were given at least 2 min and up to 10 min to recover between trials. Approximately 650 stride intervals were captured per 12 min trial.

2.4. Analysis of force plate data

Custom written MATLAB software was used to compute and process the VGRF data. The center of pressure and ground reaction force data were filtered in forward and reverse directions with a second order Butterworth filter with a cut off of 15 Hz. A 20 N threshold was used for the identification of the start and end of each foot fall, signal below this threshold was considered to be noise.

Eight gait cycle variables were investigated: stride interval and length, step interval and length, and, from the VGRF profile, the impulse, first and second peak forces, and the trough force. Stride interval was defined as starting with the onset of the heel strike of one foot and finishing with the onset of the next heel strike of the same foot. Step interval was defined as starting with the heel strike of one foot and finishing with the subsequent heel strike of the other foot. Step length was calculated by multiplying the step interval by the average belt speed for that interval and adding (or subtracting as appropriate) the difference in distance between the two heel strikes used for the calculation of step interval. Stride length was calculated similarly, multiplying stride interval by the average belt speed and adding (subtracting) the difference in distance between the successive heel strikes of the limb. Impulse is the area under the force time curve, first and second peak forces were taken as the maximum vertical ground reaction force produced during the force absorption and generation phases of stance, respectively. Trough force was the force at the minima between the first and second peaks.

2.5. Data analysis

The mean, coefficient of variation (CV—standard deviation divided by the mean), and the strength of long range correlations (α) were calculated for the time series of each dependent variable. CV quantifies the amount of variability of the time series and does not reflect the structure of stride-to-stride fluctuations. Long range correlations on the other hand provide a measure of the structure of the variability of the time series. Stronger correlations indicate a more predictable time series whereas weaker correlations indicate a less predictable time series where any given stride interval is less dependent on the stride intervals preceding it.

Long range correlations of the time series data were calculated using detrended fluctuation analysis (DFA [15]). Briefly, this method forms an accumulated sum of the time series, sections it into windows ranging in length from 4 to $N/4$ data points (where N is the total number of data points in the time series) and the log of the average size of fluctuation for a given window size is plotted against the log of the window size. The slope of this line, α, is the value returned by the DFA algorithm (see Fig. 1). This method avoids the spurious detection of correlations that are artifacts of nonstationarity in the time series [16]. An α value of 0.5 corresponds to a white noise process; α greater than 0.5 and less than (or equal to) 1.0 indicates persistent long range correlations; α less than 0.5 indicates persistent long range anti-correlations.

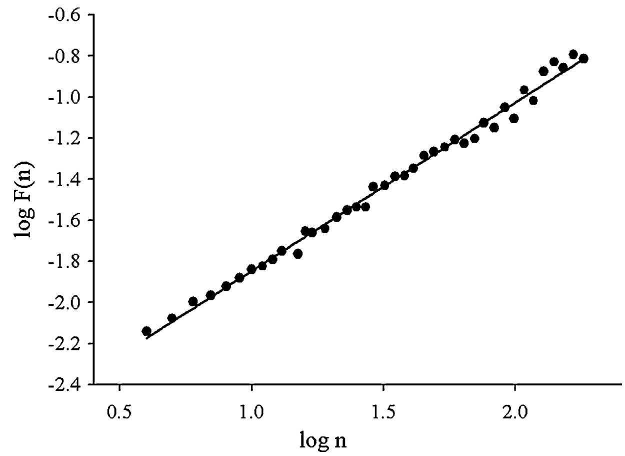

Fig. 1. Slope of line (α) relating log of average window size, n, to log of average fluctuation size, $F(n)$, for a representative trial.

The mean, CV, and α for each variable were calculated for each trial. The effects for each dependent variable were then examined using a two way (leg by speed) repeated measures ANOVA. Non-linear regression was performed on the DFA results to test for the presence of U-shaped curves. Post hoc analysis was carried out using the Tukey post hoc test and results are reported as significant if $p < 0.05$.

3. Results

Table 1 provides an overview of the ANOVA results. Long range correlations were present in all of the gait cycle variables examined. With the exception of the DFA of step interval, there were no significant differences in mean, CV or DFA between the legs for any of the gait cycle variables investigated. In the case of step interval, the long range correlations for the right leg were slightly but significantly higher than for the left leg (0.71 versus 0.68, respectively).

Fig. 2 illustrates the significant speed effect for all gait cycle variables. Stride and step interval, impulse, and trough force decreased while stride and step length, peak first and second peaks increased with increasing speed. In all cases post hoc testing revealed significant differences between each pair wise combination.

Table 1
Main effects of speed on all dependent variables from analysis of variance

	Mean		S.D.		CV		DFA	
	F(4,40)	p	F(4,40)	p	F(4,40)	p	F(4,40)	p
Stride interval (s)	217.56	<0.05	14.83	<0.05	6.37	<0.05	3.12	<0.05
Stride length (m)	323.24	<0.05	1.54	n.s.	5.95	<0.05	3.12	<0.05
Step interval (s)	216.03	<0.05	22.89	<0.05	9.75	<0.05	5.01	<0.05
Step length (m)	497.94	<0.05	1.92	n.s.	10.43	<0.05	1.50	n.s.
Vertical impulse (N s)	155.13	<0.05	8.99	<0.05	3.18	<0.05	5.16	<0.05
Force at first peak (N)	87.21	<0.05	7.84	<0.05	2.0	n.s.	0.14	n.s.
Force at second peak (N)	105.91	<0.05	10.57	<0.05	6.55	<0.05	0.77	n.s.
Force at trough (N)	271.81	<0.05	7.94	<0.05	14.22	<0.05	0.47	n.s.

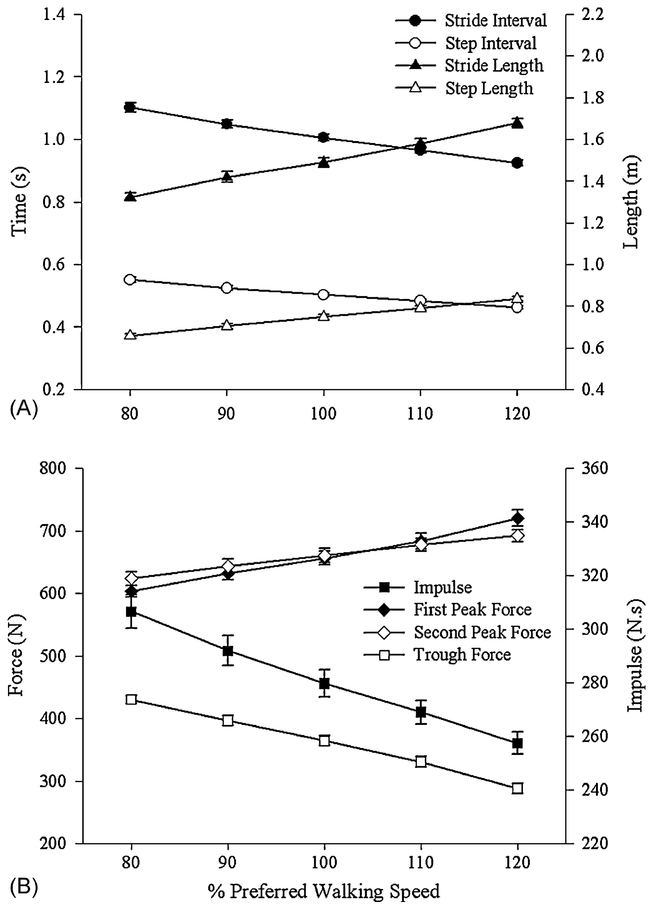

Fig. 2. (A) Group mean values for stride interval, step interval, stride length and step length vs. walking speed. (B) Group mean values for impulse, first and second peak forces and trough force vs. walking speed.

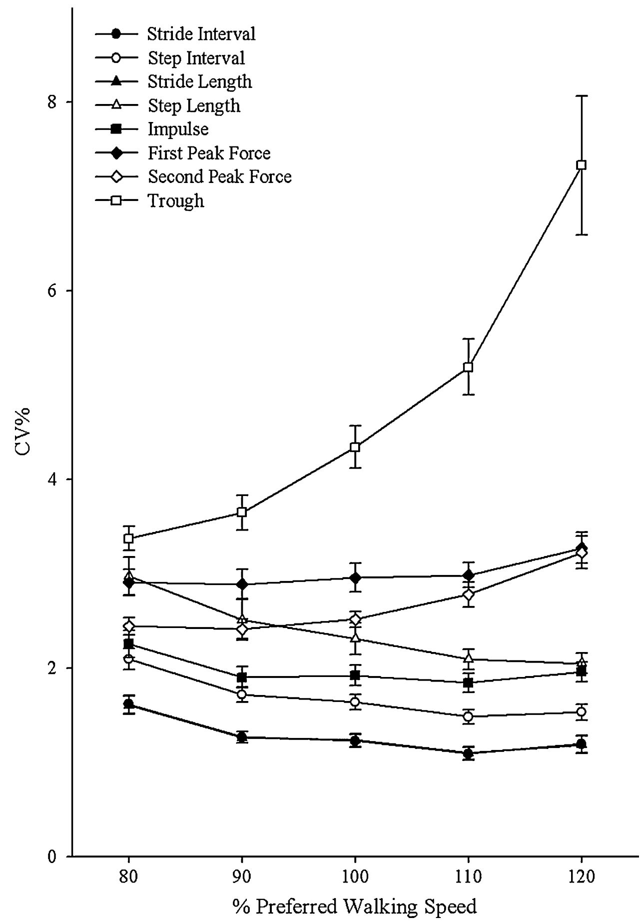

Fig. 3. Group CV for all variables vs. walking speed.

3.1. Amount of variability

Fig. 3 illustrates significant decreases in CV for step and stride interval, step and stride length and impulse, with the slope of the curve being steepest between 80% and 90% of PWS in all cases. For step and stride interval, and stride length, post hoc tests revealed significant differences between 80% of PWS and all other speed conditions. CV of step length decreased significantly between 80% and the three fastest walking speeds, where as for impulse there was a significant decrease from 80% to 110% of PWS only. CV of both second peak force and trough force increased, with significant increases occurring from the slowest three speeds to the fastest speed for second peak force. In the case of trough force, there was a significant increase in CV from all speeds to 120% of PWS, as well as from 90% to 110% of PWS.

3.2. Structure of variability

Significant speed effects were seen for α values of step and stride interval, stride length, and impulse with the α values of these variables and step length following a U-shaped pattern of change with increasing speed (Fig. 4). For stride interval and length there was a significant reduction in the strength of long range correlations from 80% to 110% of PWS. For step interval, there was a significant decrease from 80% to both 100% and 110% of PWS. In addition, for impulse, there were also significant differences between 80% and both 110% and 120% of PWS as well as between 90% and 110% of PWS.

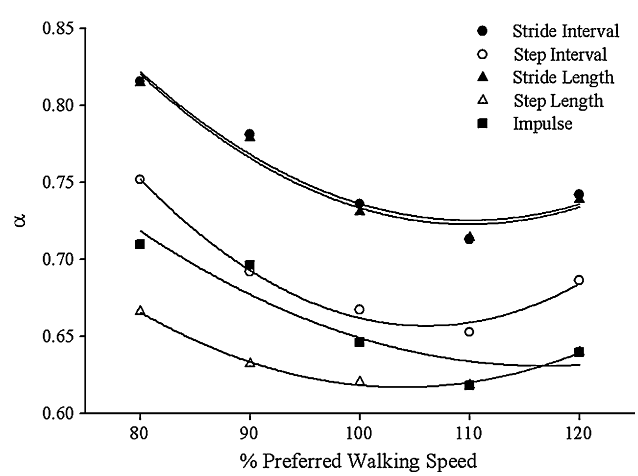

Fig. 4. Group α values for stride interval, step interval, stride length, step length and impulse vs. walking speed.

Second order polynomial curves were fit to the DFA scaling exponents for the five gait cycle variables that demonstrated a curvilinear change with speed. For stride and step interval, stride and step length, and impulse, adjusted r-squared values of 88%, 97.5%, 80.8%, 98.8%, and 75.4% were observed, respectively. For all variables except impulse, the minimum fell between 100% and 110% of PWS. In the case of impulse, the minimum was between 110% and 120% of PWS. While only step interval and step length had significant quadratic components, these adjusted r-squared values indicate that the data are well fit by a second order polynomial, and in all cases r-squared values for linear fits were smaller.

3.3. Follow-up experiment

Fig. 4 suggests that had a broader range of speeds been examined, the U-shaped curve for DFA would be more pronounced. In order to examine this possibility we performed a post hoc data collection using the same protocol but over an increased range of walking speeds: ±20% and 40% of PWS (i.e. 60%, 80%, 100%, 120%, and 140% of PWS). Data were collected from 10 non-smoking healthy participants (age = 27.4 ± 4.0 years; height = 166.6 ± 3.8 cm; weight = 62.2 ± 5.8 kg), some of whom had participated in the original data collection. The same exclusion criteria were used for these participants, thus, they were of similar fitness level to the original participants. Data were collected during 6 min trials at each speed. While it has been shown that at least 8 min of data are required in order to achieve reliable estimates of α [17], the top speed of 140% made collecting data for a longer period of time prohibitive. In all other respects, the methods were identical to that employed in the initial data collection. The pattern of results for the post hoc data collection was consistent with that of the original data. Because the motivation for the additional data collection was to clarify the initial findings for DFA, we present only the DFA results.

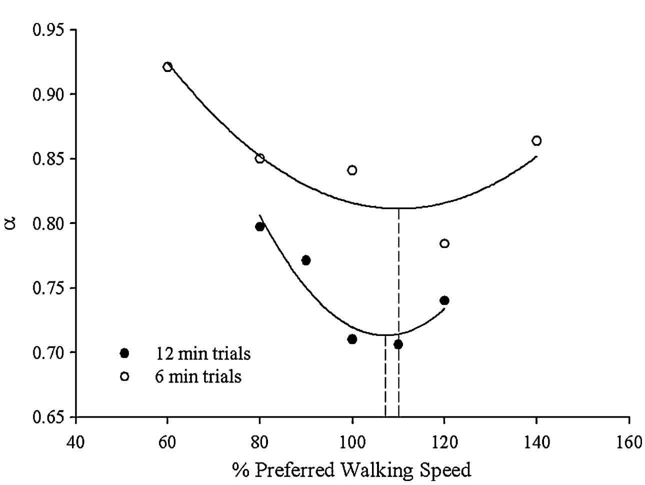

Fig. 5. Values for α for stride interval for both initial and post hoc data collections.

The DFA scaling exponents for the additional data across the five variables demonstrated U-shaped curves with speed that was similar to that of the initial data collection. Fig. 5 shows the DFA results for stride interval versus speed for both experiments separately.

4. Discussion

In this study we examined the long range correlations in multiple gait cycle variables during walking over a range of speeds. Our two main findings are that long range correlations are present in all of the gait cycle variables assessed in this study; and there are distinct U-shaped patterns of change in the strength of the correlations of several different gait cycle variables with speed that are anchored to the preferred walking speed. The CV of the majority of variables (stride interval, step interval, stride length, step length, impulse) decreased with speed. The implication of this result is that the gait cycle becomes more consistent as speed increases [3].

The α values of stride and step interval, stride and step length, and impulse all exhibit a curvilinear change with speed, the minima consistently falling between 100% and 110% of PWS. Significant quadratic trends were seen for the α values of step interval and step length but not of stride interval and stride length (although the p-values for these variables did come close to reaching significance). A similar pattern of DFA results was observed for step interval, stride and step length and impulse. While similar U-shaped curves are apparent for both sets of data, the α exponents for the post hoc data are larger than those of the original data collection (Fig. 5). To examine the possibility that this effect was related to trial length (cf. [17]), DFA was performed on the first 6 min of the original 12 min walking trials. There was no difference in the average size of α when only the first 6 min (compared with the entire 12 min) of the trial was examined. Therefore, it is likely that the relatively higher α values observed for the 6 min post hoc trials is related to influences other than trial length.

Examination of the literature on long range correlations in the walking stride interval of young healthy adults reveals that there is a large study to study variation in the average size of α. Hausdorff and colleagues have reported average values of α for this population of 0.76 [18], 0.9 (at preferred walking speed) [1], 0.88 [6], and Pierrynowksi et al. have reported $\alpha = 0.66$ for the right limb and $\alpha = 0.69$ for the left limb [17]. Thus, it is likely that there are factors other than speed and general health of the neuromuscular apparatus that affect the average size of α. The amount of time participants are required to walk (or run) for has an influence on the speed at which participants choose to transition between walking and running [19], thus, we can speculate that informational constraints (such as the amount of time participants anticipate walking for) may also have an influence on the scaling behavior of gait cycle fluctuations.

One explanation for the overall U-shaped pattern of change for long range correlations with increasing speed is that this finding relates to the increasing degree of constraint encountered by the neuromuscular apparatus at non-preferred speeds. Statistically, a reduction in strength of long range correlations indicates that any given stride is less dependent upon all preceding strides [1]. Further, the relatively larger number of time scales present in the motor output (as indicated by a decrease in long range correlation) is consistent with the proposition that there are a larger number of independently controllable system elements contributing to the motor output (e.g. [20,21]). As such, as individuals are required to walk at increasingly non-preferred speeds, the number of available options for solving the coordination problem of walking decreases and the gait cycle becomes increasingly constrained. Alternatively, this suggests that the PWS is more readily adaptable than other walking speeds. While it is impossible based on our findings to speak to the specific interactions of the sub-systems that contribute to this, in terms of physical constraints, increasing walking speed is associated with an increase in muscle stress, particularly of the dorsi-flexors and plantar flexors [22,23], and a saturation of stride length [24]. It is reasonable to speculate that other aspects related to the control of locomotion are also more constrained at non-preferred speeds and that the collective result of this is reflected in a more regular motor output.

The reduction in long range correlations at the PWS may also result from improved stability associated with walking at resonance. When individuals walk freely (i.e. at their PWS), they naturally select a stride frequency that is the same as the predicted eigenfrequency of the leg [10,12]. It has also been demonstrated that a rhythmic movement carried out at resonance has greater cycle to cycle reproducibility and stability [25] than movements at other frequencies. Because step frequency increases with increasing walking speed, walking at the resonant frequency of the limb only occurs naturally at the PWS, even though there are preferred step frequencies for all other speeds. Thus, the PWS is that at which the locomotor system should be most stable and the reduced strength of long range correlations at the PWS may reflect this enhanced stability.

Interestingly, our results appear to be in conflict with those of Goodman et al. [26], who showed that the number of active degrees of freedom required to capture the dynamics of pendulum swinging was reduced at the resonant frequency. This suggests that oscillatory movement at resonant frequency improves the predictability of the movement output, which contrasts with our results for walking. However, there are a number of differences between our study and that of Goodman et al. [26], the most obvious of which is that the task of walking is inherently more unstable and complex than that of swinging a pendulum about the wrist [3]. While stability may be maximized in both cases under the condition of preferred parameterization of the task, in the case of pendulum swinging the only way in which the task changes is that more force must be applied to swing the pendulum faster or more damping to swing the pendulum slower. The consequences of the central nervous system not compensating for the loss of stability in the wrist-pendulum system are negligible. This is clearly not the case in locomotion. While changing the speed of locomotion may require additional force production or damping as appropriate, the destabilizing effects of this internal perturbation also need to be accounted for. As participants are forced to walk at speeds increasingly different from preferred, it becomes necessary to more actively control the movement output which may increase the degree of structure present in our data. At slower speeds this may be particularly apparent as the mediolateral excursions of the center of mass increase [27]—keeping the center of mass over the support limb may therefore require a greater degree of active regulation.

One limitation of this study is that we were restricted to the use of a treadmill to collect continuous ground reaction force data (and thus the range of gait cycle variables examined). It has been shown that while mechanically there is no theoretical difference between over-ground and treadmill locomotion [28], walking on a treadmill stabilizes the locomotor output [29]. It is likely that the constantly driven speed of the treadmill does influence the scaling behavior of gait cycle behavior and future research should include a direct comparison of over-ground versus treadmill walking on the long range correlations of the gait cycle. Other avenues of future research could include an investigation of the influence of systematically altering constraints (other than gait speed) on long range correlations to examine the proposition that strength of long range correlations is related to the degree of constraint experienced by the neuromuscular apparatus.

In summary, we have shown that long range correlations are present in a range of gait cycle variables during unconstrained walking on a treadmill. In five out of eight gait variables investigated, α values followed U-shaped curves as a function of walking speed, the minima of which fell between 100% and 110% of PWS. These findings are consistent with those previously shown in running [2] and support the hypothesis that reduced long range correlations at preferred locomotion speeds is reflective of enhanced stability and adaptability at these speeds.

Acknowledgements

The authors would like to thank Nori Okita and Tim Benner for their technical support, and the anonymous reviewers for their helpful comments.

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