Stride Interval Dynamics Are Altered when Two Individuals Walk Side by Side

Jeff A. Nessler, Tomas Gonzales, Eric Rhoden, Matthew Steinbrick, and Charles J. De Leone

The purpose of this study was to examine the effects of interpersonal synchronization of stepping on stride interval dynamics during over-ground walking. Twenty-seven footswitch instrumented subjects walked under three conditions: independent (SOLO), alongside a partner (PAIRED), and side by side with intentional synchronization (FORCED). A subset of subjects also synchronized stepping to a metronome (MET). Stride time power spectral density and detrended fluctuation analysis revealed that the rate of autocorrelation decay in stride time was similar for both the SOLO and PAIRED conditions, but was significantly reduced during the FORCED and MET conditions (p=0.03 & 0.002). Stride time variability was also significantly increased for the FORCED and MET conditions (p<0.001). These data suggest that forced synchronization of stepping results in altered stride interval dynamics, likely through increased active control by the CNS. Passive side by side stepping, where synchronization is subconscious, does not appreciably alter stepping in this manner.

Keywords: biomechanics, motor control, neurophysiology, rehabilitation

When normal human gait is analyzed over hundreds of strides, stride time does not vary randomly, but exhibits a pattern that is consistent with long term correlation (Hausdorff, Peng et al. 1995; Hausdorff, Mitchell et al. 1997; Gates and Dingwell 2006; Hausdorff 2007; Damouras, Chang et al. 2009; Jordan, Challis et al. 2009). Because the duration of a particular stride is related to the duration of many previous and subsequent strides, the appearance of long range correlations in stride time are indicative of an individual’s ability to regulate the timing of the gait cycle. The evaluation of stride interval dynamics has therefore become a useful approach for detecting gait pathology, as the persistence of such patterns is thought to be a hallmark of healthy locomotion. Previous research demonstrates that stride intervals become more uncorrelated or random in the elderly and in individuals with ALS, Parkinson’s, and Huntington’s diseases (Hausdorff, Mitchell et al. 1997; Hausdorff, Lertratanakul et al. 2000; Frenkel-Toledo, Giladi et al. 2005), and alterations in stride interval dynamics are related to an individual’s risk.
for fall (Guimaraes and Isaacs 1980; Hausdorff, Mitchell et al. 1997; Maki 1997; Hausdorff, Rios et al. 2001; Herman, Giladi et al. 2005). Unfortunately, because gait analysis yields data sets that are relatively small in comparison with other phenomena, it is difficult to reliably establish the presence of long range correlations (Maraun, Rust et al. 2004; Damouras, Chang et al. 2009). However, estimates of scaling exponents can still provide a meaningful analysis of statistical persistence and are therefore relevant to the evaluation of gait cycle timing (Damouras, Chang et al. 2009). In particular, study of stride time dynamics could have implications for gait rehabilitation and may lend insight to the control of bipedal locomotion (Hausdorff, Peng et al. 1995; Hausdorff, Purdon et al. 1996; Hausdorff, Mitchell et al. 1997; Frenkel-Toledo, Giladi et al. 2005; Gates, Su et al. 2007; Hausdorff 2007; Damouras, Chang et al. 2009).

Stride interval dynamics can be evaluated through detrended fluctuation analysis (DFA) and power spectral density analysis (PSD). Both techniques have been used previously for studying the stride to stride dynamics of stride time (Hausdorff, Peng et al. 1995; Hausdorff, Purdon et al. 1996; Hausdorff, Mitchell et al. 1997; Gates and Dingwell 2006; Damouras, Chang et al. 2009), and are useful for understanding patterns in behavior that persist over long intervals (i.e., many strides). Though both techniques are useful, DFA is a more convenient estimate of statistical persistence in gait data because PSD analysis is sensitive to noise and nonstationarity effects (Hausdorff, Peng et al. 1995; Damouras, Chang et al. 2009).

In general, DFA yields an estimate of the rate of decay in stride time autocorrelation, \( \alpha \), which is typically reported to be around 0.90 for healthy individuals walking normally (Hausdorff, Peng et al. 1995; Hausdorff, Purdon et al. 1996; Gates and Dingwell 2006; Jordan, Challis et al. 2009). An estimate of \( \alpha \) between 0.50 and 1.0 is consistent with the presence of long range correlations in the time series data (Hausdorff, Peng et al. 1995; Hausdorff, Purdon et al. 1996; Hausdorff, Mitchell et al. 1997; Damouras, Chang et al. 2009). PSD results in the calculation of a scaling exponent, \( \beta \), using Fourier analysis of the stride interval time series. A value of \( \beta = 0 \) is typical for completely uncorrelated data (i.e., white noise), a value of \( \beta = 1.0 \) is typical for 1/f noise (i.e., pink noise), and a value of \( \beta = 2.0 \) is typical of brown noise (Hausdorff, Peng et al. 1995). Previous analyses of gait data have reported \( \beta \) to be between 0.59 and 0.90 (Hausdorff, Peng et al. 1995; Hausdorff, Purdon et al. 1996; Gates and Dingwell 2006), and theoretically, for a stationary time series of infinite length, \( \alpha = (1 + \beta)/2 \) (Hausdorff, Purdon et al. 1996; Heneghan and McDarby 2000).

The study of interpersonal synchronization during side by side, paired walking presents a unique set of challenges when compared with other forms of coordinated movement. While a variety of coordinated, rhythmic movements within the same person (i.e., intrapersonal synchronization) can be accurately described by the Haken Kelso Brunz coupled dynamic oscillator model (Haken, Kelso et al. 1985; Schmidt, Bienvenu et al. 1998; Richardson, Marsh et al. 2007; Richardson, Lopresti-Goodman et al. 2008), interpersonal synchronization suffers from relatively weak attractor strength. In such cases, the Haken Kelso Brunz model is limited in its ability to predict synchronizing behavior. This is particularly true of side by side walking, as previous analyses of both intentional and unintentional synchronization demonstrates that this model does not readily apply (van Ulzen, Lamoth et al. 2008; van Ulzen, Lamoth et al. 2010). However, reduced attractor strength notwithstanding, both intentional and unintentional synchronization
during paired walking have been shown to result in interpersonal synchronization to varying degrees, leading to significant alterations in step kinematics (Nessler, DeLeone et al. 2009; Nessler and Gilliland 2009; Nessler and Gilliland 2010). Variations in spatial kinematics of stepping suggest that stride interval dynamics are likely also altered under paired walking conditions, and study of these temporal characteristics may contribute to an overall understanding of this behavior as it relates to the control of locomotion.

In particular, analysis of stride interval dynamics during side by side walking may lend insight to the origins of statistical persistence in the healthy stride interval time series. Such patterns might be the result of processes within the CNS, or simply the result of the nonlinear dynamics of the locomotor system, independent of CNS control. On the one hand, stride times become more random following CNS degeneration and with conditions that present increased challenge to control of stepping (Hausdorff, Mitchell et al. 1997; Buzzi, Stergiou et al. 2003; Herman, Giladi et al. 2005; Kang and Dingwell 2009). In addition, previous research suggests that certain external stressors can affect long range correlations in stride time. For example, stride interval statistical persistence in healthy individuals is reduced when subjects are asked to walk at treadmill speeds other than their preferred walking speed (Hausdorff, Purdon et al. 1996; Jordan, Challis et al. 2009). However, simulations of bipedal locomotion using a well-known passive dynamic walking model suggest that this persistence might simply arise from the inherent biomechanics of the locomotor system, rather than originating within the central nervous system (Kurz and Stergiou 2005; Kurz, Stergiou et al. 2005; Gates, Su et al. 2007).

Analysis of stride interval dynamics may also have implications for situations where synchronization with an external signal might be used to influence or promote correlations in stride time. For example, rhythmic auditory stimulation is a promising therapy that has been used to improve gait function in multiple patient populations (Thaut, McIntosh et al. 1996; Frenkel-Toledo, Giladi et al. 2005; Hausdorff, Lowenthal et al. 2007; Roerdink, Lamoth et al. 2007). However, forced synchronization with an external cue requires increased CNS activity in the control of gait, which may result in step kinematics that differ from those exhibited under normal walking conditions (Hausdorff, Purdon et al. 1996; Nessler and Gilliland 2010). In addition, a metronome is unable to reproduce the variability that is inherent in normal human gait, and synchronization with an unvarying signal has been shown to result in stride interval time series’ that are random and resemble those of neurologically diseased patients (Hausdorff, Purdon et al. 1996). Replacing the metronome beat with a variable, external cue such as the step interval of a second individual during side by side walking may yield a different outcome (Nessler, DeLeone et al. 2009; Nessler and Gilliland 2010). In addition, spontaneous or unintentional synchronization may be preferable to the intentional or forced case where increased CNS control is employed.

The purpose of this study was to examine the effects of intentional and unintentional synchronization on stride interval dynamics during side by side, paired walking and walking to the beat of a metronome. For this analysis, stride interval dynamics were defined by estimates of \( \alpha \) and \( \beta \), mean stride time, and stride interval coefficient of variance. Estimates of statistical persistence in stride time (\( \alpha \)) were also compared with leg length differences across subject pairings to estimate the effects of within-pairing differences in preferred walking speed on
these values. Based upon existing evidence, it was hypothesized that intentional or forced synchronization to a partner would result in reduced statistical persistence in stride times (i.e., reduced $\alpha$ and $\beta$) when compared with normal walking and walking with unintentional synchronization (Hausdorff, Purdon et al. 1996; Nessler and Gilliland 2010). In addition, $\alpha$ and $\beta$ were expected to be greater (i.e., greater persistence) during intentional synchronization with a partner when compared with the metronome walking condition. Finally, stride interval variability was expected to increase with intentional synchronization.

Methods

Subjects

A convenience sample of 27 pairs of male and female subjects were recruited from the local student population ($n = 52$, age $23.2 \pm 3.0$ year, mass $69.0 \pm 15.6$kg, height $1.7 \pm 0.1$m). Subjects were paired socially, as each participant was asked to select an acquaintance to serve as their partner. Subjects were not intentionally paired with regard to leg length, preferred walking speed, or any other biomechanical factor. All subjects were free of musculoskeletal or neurological conditions that might have affected gait. Approval was obtained through the Institutional Review Board, and all subjects gave their informed consent before participation. Subjects were kept naïve as to the purpose of the experiment until data collection had ended.

General Procedures

For each pair, one subject was instrumented for data collection by affixing a foot-switch sensor to the sole of their shoe at the heel (Biopac Systems Inc., TSD11A). Before formal data collection, subjects were asked to walk for 15 s while data were collected to ensure proper placement of the sensor. The second subject was not instrumented, and served only to facilitate synchronization during side by side walking trials. Data from the footswitch sensor were acquired at 120 Hz via netbook computer running MATLAB’s Data Acquisition Toolbox (R2009b, Natick, MA), which was placed in a small backpack worn by the first subject. Wires extending from the sensors to the PC were taped to the subject’s leg to avoid any alteration to normal locomotion. Data collection took place outside of the laboratory, and subjects were required to walk over-ground around the university athletic track. Care was taken to ensure that other individuals were not using the track to avoid any sudden changes in direction by the subjects. Subjects wore their personal athletic shoes for all trials.

Each of the 27 instrumented subjects (i.e., 1 subject from each of the 27 pairs) was instructed to walk under three conditions. For the SOLO condition, subjects walked independently at their own preferred walking speed. For the PAIRED condition, subjects walked side by side with their partner, but were kept naïve as to the purpose of this experiment and were given no instruction regarding synchronization. For the FORCED condition, subjects again walked side by side, but were instructed to intentionally synchronize their stepping with in-phase coordination (i.e., right foot of subject 1 with right foot of subject 2). All trials took place in this order so as to minimize the possibility that the Forced condition would affect performance.
of subjects during the Paired condition by prematurely drawing attention to their partner’s steps. In addition to the SOLO, PAIRED, and FORCED trials, 6 of the 27 instrumented subjects were asked to step to the beat of a metronome that was set to their preferred walking speed, as estimated from their performance during the SOLO trial. Each trial was 8 min in duration.

Because the second subject in each pairing was not instrumented, it was not possible to assess the amount of synchronization that occurred between partners. However, previous research consistently demonstrates that subjects will synchronize step frequency on average for 99% of the trial during the FORCED condition, and approximately 50–60% of the trial during the PAIRED condition (Zivotofsky and Hausdorff 2007; van Ulzen, Lamoth et al. 2008; Nessler, DeLeone et al. 2009; Nessler and Gilliland 2009).

Data Analysis

Data analysis was performed using custom routines developed in MATLAB. Data analysis began with the calculation of stride times by finding the time between consecutive footswitch contacts with the ground (i.e., closing of the switch). Stride time data sets were then visually inspected by constructing and viewing time series line graphs for each trial to determine if a data file had a large number of outliers (i.e., greater than 5 outliers), as missing footswitch signals would result in abnormally large stride times. As a result of this prescreening analysis, all data for 3 of the original 27 pairs were discarded due to an excessive number of outliers (i.e., missing data). A median filter was then applied to the remaining data sets to remove any stride interval value that was greater than 3 standard deviations above or below the median for each time series. From these data, mean stride interval time, stride interval coefficient of variance, the rate of decay of stride time autocorrelation (α), and the scaling exponent (β) for the power spectral density distribution were calculated. For α, detrended fluctuation analysis (DFA) was applied to each time series. The following is a relatively brief description of this procedure, as this analysis has been described in greater detail previously (Hausdorff, Peng et al. 1995; Maraun, Rust et al. 2004; Damouras, Chang et al. 2009).

First, stride interval time series of length N were integrated:

\[
y(k) = \sum_{i=1}^{k} [x(i) - x_{avg}]
\]

where \(x(i)\) denotes the \(i^{th}\) stride interval, and \(x_{avg}\) denotes average time series stride interval. The time series was then divided into equal, nonoverlapping boxes of length \(n\). A least squares line was then fit to the data contained within each box of length \(n\), yielding a sequence of trendlines \((y_n)\) of length \(N/n\). The average fluctuation, \(F(n)\), of the integrated time series about the trendline sequence \((y_n)\) was then calculated over a range of box sizes:

\[
F(n) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [y(i) - y_n(i)]^2}
\]
Finally, log $F(n)$ was plotted against log $n$. The presence of a linear relationship between these variables allows for the estimation of $\alpha$ (the rate of decay of autocorrelation) by calculating the slope of the least squares fitted line. Selection of an appropriate range for $n$ is an important factor for this analysis, though this range is not standardized across research groups. To address this disparity, Damouras et al. (2009) recommended a range for $n$ of 16 to $N/9$ (where $N$= number of strides for a particular data set) following careful analysis of stride interval data from both healthy and impaired individuals as they walked under conditions very similar to those of the current analysis (Damouras, Chang et al. 2009). This recommended range was therefore used here. Calculation of $\beta$ began with use of MATLAB’s fast Fourier transformation algorithm to calculate the squared Fourier transform amplitude of each stride interval time series. A log-log plot of this result vs. frequency was then generated, and a least squares line fitted to the data. The negative slope of this line defines the scaling exponent, $\beta$, and represents the distribution of the power spectrum.

To further ensure that any observed stride interval correlations did not simply arise by chance, surrogate data were generated and analyzed in the manner described above. For each subject, the stride interval time series for the SOLO condition was randomly shuffled as described previously (Theiler, Eubank et al. 1992; Hausdorff, Peng et al. 1995; Gates and Dingwell 2006). This process was repeated 10 times, yielding 10 random permutations of stride time for each subject, and a mean $\alpha$ and $\beta$ were then calculated as a representation of the chance occurrence of patterns in stride time. Consistent with previous analyses of a similar nature, a difference of more than 3 standard deviations between the values obtained from the surrogate and original data were considered significant (Theiler, Eubank et al. 1992; Hausdorff, Peng et al. 1995; Hausdorff, Mitchell et al. 1997; Gates and Dingwell 2006). Such a result would therefore provide support for the presence of statistical persistence in the stride interval.

Previous investigators have noted that stride interval dynamics are altered when an individual walks at speeds that are different from their preferred walking speed (Jordan, Challis et al. 2009). Because an individual’s preferred walking speed is related to their leg length, it is reasonable to expect that pairs of subjects with large differences in leg length would be forced to walk at speeds further from their preferred speed to synchronize, and this may have an effect on the amount of statistical persistence that is detected. Therefore, leg length differences among pairs were correlated with DFA results for both the PAIRED and FORCED condition to determine the magnitude of this effect in the current data.

Statistical analysis began with separate repeated-measures ANOVA applied to each of the four independent variables (mean stride time, stride time CV, $\alpha$, and $\beta$). Significant results were followed post hoc with paired $t$ tests, utilizing the Bonferroni correction for multiple comparisons with family-wise $\alpha$ set to 0.05. In addition, single subject analysis was performed on stride time data utilizing the Model Statistic procedure (Bates, Dufek et al. 1992). In short, stride times for 30 strides were taken at random from the SOLO, PAIRED, and FORCED condition for each subject, and these data were compared across trials as though they were obtained from multiple subjects.
Results

Statistical analysis of $\alpha$ revealed that statistical persistence in stride interval was not significantly different between the SOLO and PAIRED conditions, but was significantly reduced during the FORCED condition ($\alpha=0.92 \pm 0.20, 0.84 \pm 0.17$, and $0.70 \pm 0.20$, respectively, $p = .002$ Table 1). An example of this behavior for a typical subject is illustrated in Figure 1. Least squares lines fitted to the plot of $\log n$ vs. $\log F(n)$ were statistically significant in all cases ($r^2 = .93 \pm 0.05, 0.91 \pm 0.07$, and $0.90 \pm 0.09$, respectively, $p < .001$). Fits of the least squares lines ($r^2$) appeared to be decreased for the PAIRED and FORCED conditions on average with respect to the SOLO condition (e.g., Figure 1), but this difference was not statistically significant ($p = .126$). Results of correlation analysis of leg length differences between partners and $\alpha$ were not statistically significant ($r=-0.06$ and -0.30, $p = .821$ and 0.142 for the PAIRED and FORCED conditions, respectively).

Similar to $\alpha$, statistical analysis of $\beta$ revealed scaling exponents that were not different between the SOLO and PAIRED conditions, but were significantly reduced for the FORCED condition ($\beta=0.49 \pm 0.17, 0.42 \pm 0.18$, and $0.37 \pm 0.25$, for the SOLO, PAIRED, and FORCED conditions, $p = .030$, Table 1). An example of differences between the SOLO and FORCED condition for a typical subject is illustrated in Figure 2. Estimation of $\alpha$ using the theoretical relationship $\alpha=(1+\beta)/2$ yielded values that were only moderately correlated with the experimental values obtained for $\alpha$ ($r = .51$). In addition, overall values obtained for $\beta$ in the current study were slightly lower than expected, and exhibited relatively high variability when compared with $\alpha$.

Analysis of 10 random permutations of stride times for each subject’s SOLO walking performance yielded an average $\alpha$ of $0.50 \pm 0.03$ and an average $\beta$ of $0.01 \pm 0.04$. These values are consistent with uncorrelated data (i.e., white noise) and were significantly less than those obtained for the original data for all three walking trials ($p < .001$). On average, $\alpha$ and $\beta$ measured for each subject during the SOLO

Table 1  Effects of Side by Side Walking on Temporal Measures of Gait

<table>
<thead>
<tr>
<th></th>
<th>SOLO</th>
<th>PAIRED</th>
<th>FORCED</th>
<th>METRONOME</th>
<th>SURROGATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stride-Interval</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correlations, $\alpha$</td>
<td>0.92 ± 0.20</td>
<td>0.84 ± 0.17</td>
<td>0.70 ± 0.20†*</td>
<td>0.52 ± 0.14†</td>
<td>0.50 ± 0.03†</td>
</tr>
<tr>
<td>Power Spectral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density, $\beta$</td>
<td>0.49 ± 0.17</td>
<td>0.42 ± 0.18</td>
<td>0.37 ± 0.25†</td>
<td>0.09 ± 0.39†</td>
<td>0.01 ± 0.04†</td>
</tr>
<tr>
<td>Mean Stride</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interval (sec)</td>
<td>1.02 ± 0.07</td>
<td>1.05 ± 0.07†</td>
<td>1.04 ± 0.05</td>
<td>1.09 ± 0.04†</td>
<td></td>
</tr>
<tr>
<td>Stride Interval</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (%)</td>
<td>1.8 ± 0.60</td>
<td>1.8 ± 0.60</td>
<td>2.2 ± 0.90‡*</td>
<td>2.2 ± 1.13</td>
<td></td>
</tr>
</tbody>
</table>

Values are mean ± SD

†differs significantly from SOLO condition at $p < 0.05$

*differs significantly from PAIRED condition at $p < 0.05$
Figure 1 — Single subject representative data illustrating the effects of walking condition on statistical persistence of stride interval (\(\alpha\)). SOLO and PAIRED conditions resulted in scaling exponents (i.e., slope) that were not significantly different, while forced synchronization and synchronization to a metronome (not pictured) resulted in significantly reduced \(\alpha\). All walking conditions resulted in significantly greater stride interval correlation when compared with surrogate data. Surrogate data were generated by random permutation of the stride interval time series.

walking trial were approximately 5 standard deviations above the values obtained for the mean surrogate data for that subject.

DFA and PSD analysis for performances during which subjects matched their stepping to the beat of a metronome revealed little to no statistical persistence (\(\alpha=0.52 \pm 0.14, \beta=0.09 \pm 0.39, n=6\)). These results were similar to those obtained for surrogate data analysis, but were different from analysis of the other walking trials.

Mean stride times for the PAIRED condition were significantly increased with respect to the SOLO condition (1.02 ± 0.07 vs 1.05 ± 0.07, \(p=.001\), Table 1), but stride times for the FORCED condition were not different from either the SOLO or PAIRED conditions (\(p=.103\) and 0.379 respectively). Single subject analysis using the Model Statistic procedure indicated significant differences in stride time for 23 of 24 subjects when the SOLO condition was compared with the FORCED condition. Similarly, 21 subjects and 20 subjects demonstrated significant differences in stride time between the SOLO and PAIRED conditions and PAIRED and FORCED conditions, respectively. Finally, stride time variability was significantly increased for the FORCED condition when compared with both the SOLO and PAIRED condition (CV = 1.8 ± 0.6 and 1.8 ± 0.6 vs 2.3 ± 1.1\%, \(p=.004\)).
Figure 2 — Example of the effect of walking condition on power spectral density (PSD) analysis (slope = $\beta$) of the stride interval time series for the SOLO condition (Left) and the FORCED condition (Right). These plots from a representative subject illustrate that $\beta$ was significantly reduced during the FORCED condition.
Discussion

The primary results of this analysis are threefold. First, intentional synchronization with a partner appears to result in stride time fluctuations that are significantly more random than normal walking, yet appear to be more persistent than surrogate data or walking in step with a metronome. Second, the PAIRED condition in which unintentional synchronization was likely to occur yielded scaling exponents for stride time that were not statistically different from those estimated from normal walking trials (\(\alpha=0.92 \pm 0.20\) vs. 0.84 \(\pm\) 0.17, \(p = .119\)). Third, stride time coefficient of variance was similar for both the SOLO and PAIRED conditions, but was significantly increased for the FORCED condition (1.8 \(\pm\) 0.60 and 1.8 \(\pm\) 0.60 vs. 2.2 \(\pm\) 0.90%, \(p = .004\)). Taken together, these results suggest that increased concentration and voluntary control of stepping results in increased stride time variability and a reduction in long range correlations in stride time, while paired walking in which synchronization is subconscious does not yield the same effect. These data are consistent with those of previous analyses (Hausdorff, Purdon et al. 1996; Nessler and Gilliland 2010).

It is difficult to establish the presence of long range correlations with time series of reduced length primarily because estimates of \(\alpha\) exhibit decreased test-retest reliability with fewer data points. However, the data sets obtained from 8 min of overground stepping were sufficient to determine the presence of statistical persistence in the current experiment for two reasons. First, the current values obtained for \(\alpha\) are consistent with those reported previously and are significantly greater than those obtained using surrogate data and walking to the beat of a metronome (Hausdorff, Purdon et al. 1996; Hausdorff, Mitchell et al. 1997; Gates, Su et al. 2007). Second, Damouras et al. (Damouras, Chang et al. 2009) estimated a standard error of the measure for \(\alpha\) of approximately 0.055 for data sets of comparable size to those used here. The observed difference in walking performance between the SOLO and FORCED condition, as indicated by \(\alpha\) in the current data, was 0.22, or approximately 4 times the \(SEM\) that can reasonably be expected from this analysis.

Though significant decreases in \(\alpha\) and \(\beta\) were noted across walking conditions, estimates for \(\beta\) were reduced overall in comparison with previous analyses of a similar nature (Hausdorff, Peng et al. 1995; Hausdorff, Purdon et al. 1996; Hausdorff, Mitchell et al. 1997; Gates, Su et al. 2007). This reduction in \(\beta\) is likely due to increased sensitivity to noise, as estimates of \(\beta\) exhibited standard deviations that were somewhat increased in comparison with those of \(\alpha\). Estimates of statistical persistence obtained via PSD analysis are known to be more sensitive to artifacts such as noise and nonstationarity when compared with DFA. With respect to previous analyses, this increase in noise might be the result of differences in data processing procedures, such as the characteristics of the median filter applied before PSD analysis. Reduced estimates of \(\beta\) may also be due to differences in performance associated with treadmill vs. overground walking, as treadmill walking is known to reduce kinematic variability (Dingwell, Cusumano et al. 2001).

Gait Variability

While the current results demonstrate similar stride interval dynamics for both the SOLO and PAIRED conditions, previous results demonstrate that variability in
spatial kinematics of lower limb movement (i.e., estimates of maximal Lyapunov exponents, \(\lambda^*\)) are increased during the PAIRED condition (Nessler, DeLeone et al. 2009). Together, these data do not support the idea that a relationship exists between \(\alpha\) and measures of local stability for lower extremity kinematics, as described in (Jordan, Challis et al. 2009). Instead, the idea that PAIRED walking can result in an increase in spatial kinematic variability without a significant change in temporal dynamics of stepping is meaningful, as it demonstrates the “flexibility” of a healthy locomotor system. If stride time is viewed as the primary output of the locomotor system, there are likely multiple patterns of lower limb movement that will achieve a consistent stride time output. In other words, because there are several degrees of freedom to lower limb movement, there are multiple solutions to the dynamical problem of advancing the foot within a specific time frame. A healthy system is likely able to use multiple movement patterns to achieve a consistent, desired output. This flexibility is a hallmark of a more stable passive dynamic walker (Kurz and Stergiou 2005; Kurz, Stergiou et al. 2005; Kurz and Stergiou 2007), and may therefore be desirable for human locomotion.

The current results suggest that unintentional synchronization requires increased flexibility in lower limb kinematics with strict adherence to a consistent stride time. Practicing walking under these conditions may therefore have a beneficial effect for individuals at risk for fall. This idea is also supported by evidence that elderly nonfallers often demonstrate increased variability in spatial kinematics (Buzzi, Stergiou et al. 2003; Kang and Dingwell 2009), but do not always demonstrate increases in the variability of temporal kinematics (Hausdorff, Mitchell et al. 1997). Though many fall reduction interventions have been proposed and evaluated to date (Latham, Bennett et al. 2004; Baker, Atlantis et al. 2007; Harmer and Li 2008; Orr, Raymond et al. 2008; Sherrington, Whitney et al. 2008), very few have examined exercises that focus on improving the neuromechanics of gait, such as those described by Hausdorff and colleagues (Hausdorff, Nelson et al. 2001; Hausdorff, Lowenthal et al. 2007). Because increased variability and randomness of the stride interval is related to fall risk (Guimaraes and Isaacs 1980; Hausdorff, Edelberg et al. 1997; Maki 1997; Hausdorff, Rios et al. 2001; Herman, Giladi et al. 2005), and because there appears to be conflicting evidence on the effects of walking practice in general (Ebrahim, Thompson et al. 1997; Barnett, Smith et al. 2003; Latham, Bennett et al. 2004; Sherrington, Whitney et al. 2008), additional study of walking interventions is needed.

**Origins of Stride Time Correlations**

These results may provide insight for studying the origins of long range correlations in the stride interval during human gait. Previous investigators have proposed that this behavior might arise as the result of complex central nervous system control, or simply due to the nature of the nonlinear dynamics of the walking motion (Hausdorff, Purdon et al. 1996; Gates, Su et al. 2007). The latter position is supported by simulations with a properly tuned passive dynamic walker that demonstrate statistical persistence similar to that observed in healthy humans (Gates, Su et al. 2007). If stride interval correlations are mechanical in origin, decreases in \(\alpha\) that are seen under conditions of active CNS control of walking, such as when external stressors are present, may be the result of decreased reliance on the natural system dynamics in favor of increased corrective muscle activity. Such behavior is often
seen in motor learning, where individuals in the early stages of learning a motor skill often rely on active control to perform a novel task. With practice, extraneous muscle activity and corrective movements are pared away in favor of a more passive, automatic control (Milton, Small et al. 2004).

Increased age or disease may also result in a reversion of control strategy to a state where increased CNS activity is employed, possibly due to perceived instability and a fear of falling. Incidental increases in CNS activity may also be the direct result of CNS pathology. The current data suggest that something similar occurs during forced synchronization of stepping, where stride times became more variable and more uncorrelated with a more active control strategy. The fact that this appears to occur to a much lesser extent during the PAIRED condition, where synchronization is known to occur unintentionally, implicates this strategy as a primary factor. Here, increased CNS control during the forced side by side and metronome walking trials resulted in stride time fluctuations that were more random, supporting the idea that statistical persistence in stride time is consistent with conditions in which less CNS activity is applied to stepping. Such behavior may arise simply from the inherent biomechanics of the locomotor system, as supported by (Gates, Su et al. 2007).

Finally, intentional synchronization with a partner (i.e., FORCED condition) resulted in estimates for $\alpha$ and $\beta$ that were larger than those found for metronome walking both in the current data and that of previous investigators (Hausdorff, Purdon et al. 1996). Both conditions of synchronization require an increased level of concentration and therefore CNS activity while stepping. However, there are several key differences in these two conditions that may account for the observed differences in stride interval dynamics. First, unlike typical human movement, the cue from a metronome does not vary. Conversely, the external cue from a partner’s stride exhibits variability that is more consistent with normal bipedal walking. Anecdotal evidence (i.e., post data collection interviews) suggested that stepping to the beat of the metronome was perceived to be very unnatural and required more effort than that of forced synchronization with a partner. Second, interpersonal synchronization involves efforts from both individuals to match step frequency. This constant, bidirectional adaptation may require fewer corrective movements and less effort by each subject when compared with stepping with a machine that does not alter its output. Finally, side by side walking provides both visual and auditory cues of one’s partner, which may result in greater activation of the mirror neuron system (e.g., (Cochin, Barthelemy et al. 1999; Rizzolatti and Craighero 2004; Ramachandran and Altschuler 2009)).

In summary, these data demonstrate that side by side walking in which synchronization is unintentional or subconscious does not appreciably affect stride interval dynamics. Conversely, forced synchronization of stepping with a partner results in a significant increase in stride time variability and a significant decrease in both measures of long range correlation in stride time used in the current analysis ($\alpha$ and $\beta$). Forced synchronization of stepping during side by side walking however, does not affect stride interval dynamics to the extent of walking to the beat of a metronome. Together, these results suggest that increased active control of locomotion by the CNS results in a reduced ability to regulate gait cycle timing. These results are consistent with the idea that statistical persistence in stride time arise as a result of conditions of reduced CNS activity during gait and are possibly inherent to the natural biomechanics of the locomotor system.
References


