'Human paced' walking: Followers adopt stride time dynamics of leaders

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HIGHLIGHTS

• Human pacing provides a natural cue for walking.
• Fractal exponents of followers and leaders are statistically similar.
• Human pacing may facilitate gait rehabilitation.

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ABSTRACT

Isochronous cueing is widely used in gait rehabilitation even though it alters the stride-time dynamics toward anti-persistent rather than the persistent, fractal fluctuations characteristic of human walking. In the present experiment we tested an alternative cueing method: pacing by a human. To this end, we formed sixteen pairs of walkers based on their preferred stride frequency. Each pair consisted of a designated “leader” and a “follower” who was instructed to synchronize his or her steps to those of the leader. Heel strike times were detected with tiny footswitches, and Detrended Fluctuation Analysis (DFA) was applied to estimate fractal exponents of stride-time series. To ensure that the stride-time dynamics of the follower matched those of the leader, the latter was structurally modified by artificial cueing via either an isochronous metronome or a fractal metronome, in contrast to self-paced walking. Mean relative phases between followers and leaders were close to 0°, confirming that followers effectively synchronized their footfalls with those of the leaders. Mean fractal exponents were not statistically different between followers and leaders in any condition and highly correlated, suggesting that followers matched their stride-time structure to that of leaders. Our results open perspectives for alternative, more natural cueing protocols for gait rehabilitation.

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1. Introduction

Stride-time variability expressed in terms of standard deviation (SD) and coefficient of variation (CV) is greater in elderly fallers compared to non-fallers [1]. To date, gait rehabilitation protocols have therefore focused predominantly on improving step length and walking speed, and reducing overall gait variability [2]. However, gait variability is also determined by the sequencing of events, i.e. how steps are organized in time. In healthy individuals, stride-time, stride length and stride speed fluctuations are neither fully random nor entirely periodic but display persistent, long-range correlations [3–6]. Long-range correlations, as estimated by the fractal exponent α, have been proposed to discriminate populations where other, more classical variables were incapable of doing so: fallers vs non-fallers among elderly with “higher-level” gait disorders [7], or healthy young vs healthy elderly [8]. Together with the decrease of α observed in patients with neurodegenerative diseases [8,9], these results suggest that the central nervous system might be implicated in the production of long-range correlated fluctuations. Hence, in the context of gait rehabilitation protocols, improving the stride dynamics toward the level of long-range correlations seen in healthy individuals may well be as
important as improving “traditional” gait variables, such as CV and SD of stride time series.

Two explanations for the reduction of $\alpha$ with aging or disease prevail in the literature. According to the first, the alteration of fractal dynamic may be associated with a loss of optimal variability [16,17]. The second explanation pertains to an increased control of stride-to-stride regulation, leading to corrections at each step relative to the previous step [13,18]. Regardless of the true origin of these alterations, we submit that people at risk of falling would benefit from an increase of the fractal exponent of their stride-time series [7]. This hypothesis implies that it would be possible to modify the fractal exponent of stride-time series, experimentally or otherwise.

Step entrainment with external, auditory cues while walking has been widely used as a therapeutic tool to reduce gait variability in populations with neurodegenerative diseases [10,11]. However, the stride dynamics has been proven to be deeply altered when gait is paced by isochronous cues compared to being self-paced: in this case, stride-time fluctuations become anti-persistent, i.e. negatively correlated, with a sharp decrease of the $\alpha$ exponent [12–15]. Recent studies suggest that, unlike synchronization with isochronous metronomes, certain synchronization tasks are not associated with such an alteration of stride dynamics. In particular, synchronization with non-periodic metronomes seems to induce or facilitate behavioral fluctuations that match the structure of environmental fluctuations [19–22]. Recently, Kaipust et al. [23] reported that walking while listening to a chaotic metronome enhanced the fractal exponents of stride intervals in elderly, unlike listening to a periodic or random metronome. Taken together these findings suggest a “sensitivity” of human perception and motor control to fractal environments, compared to simpler (periodic) or more complicated (random) stimuli.

Nessler et al. [24] suggested that replacing the auditory metronome with a variable and more familiar environment, like another human, could represent an effective strategy in gait rehabilitation. Interpersonal synchronization occurs even unintentionally [25–27]. Thus, an elegant and simple pacing strategy might be to synchronize steps with a human partner whose stride-time series contain long-range correlations. A first necessary step in testing this possibility is to check if step synchronization with a human partner can modify the fractal exponent of stride intervals.

We measured the attainment of $\alpha_{\text{follower}}$ to $\alpha_{\text{leader}}$ in a walking task on a large treadmill. Since all participants were young and healthy, their $\alpha$’s for self-paced walking were expected to be persistent. We tested if the stride-time fluctuations in leaders effectively influenced the stride-time fluctuations in followers by adopting the following hypotheses. (1) The relative phase between leader and follower limb is close to 0°; if so, this would constitute proof that followers intentionally synchronize with leaders [28]. (2) $\alpha_{\text{follower}}$ and $\alpha_{\text{leader}}$ are significantly correlated. Indeed, if the follower is not affected by the gait variability of the leader, then $\alpha_{\text{follower}}$ is persistent even when the leader is paced by an isochronous metronome and presents anti-persistent fluctuations.

2. Materials and methods

2.1. Participants

After providing written informed consent, 24 volunteers (10 males, 14 females; age: 26.5 ± 2.8 yrs, body height: 172.42 ± 26.1 cm, body mass: 69.5 ± 12.7 kg) participated in the experiment. All were healthy and none had any neuromuscular disorder or recent injury at the time of study. The local ethics committee of the Faculty of Human Movement Sciences of VU University Amsterdam approved the experiment prior to its conductance.

2.2. Apparatus and equipment

Participants walked on a large treadmill (3 m wide, 4 m long; Bonte Technology BV, Zwolle, Netherlands) at a speed of 4.5 km/h. i.e., close to the mean preferred walking speed for healthy participants in several experiments [4–6]. Tiny footswitches (EMG force sensitive) were fixed under the right heel of participants to record heel strike moments (500 Hz). Inter-beat intervals (IBI) were generated in Matlab (Mathworks, Natwick, MA) and administered through earphones to pace the right heel strikes of leaders. Followers always wore earmuffs to prevent them from hearing the metronome beats. Participants were instructed to wear trousers and sneaker-like-shoes (with a flat sole to easily determine heel strike moments).

2.3. Tasks and instructions

In a first session, participants walked alone on the treadmill for 11 min at 4.5 km/h after a short habituation period (4 min). They were instructed to walk as naturally and regularly as possible and to look in front of them, while wearing earmuffs. This condition was repeated once yielding Session 1a and Session 1b, allowing us to assess the reliability of the fractal exponents of stride time series. Participants with similar mean stride intervals were paired in the second session, as participants with similar stride frequency were expected more likely to synchronize [24].

In the second session, participants walked behind one another (“leader/follower” configuration) in three conditions, conducted in random order, after a short habituation period (4 min). Conditions were signified via the pacing of leaders: self-paced (SP condition), no sound was audible in leaders earphones; isochronously paced (ISO condition), a regular metronome was administered, and fractally (1/f condition) paced, the beat interval series of the metronome were not regular but presented a coefficient of variation (CV) of 1% and a Hurst exponent ($H$) of 0.8. Briefly, the Hurst exponent is a scaling coefficient which links the size of the fluctuations $F(n)$ to the size of the observation windows $n$ in a power-law fashion (see Section 2.4 for further description of the method). CV and $H$ here correspond to the mean values for all participants in Session 1. In ISO and 1/f conditions, the mean beat intervals of the metronomes corresponded to the mean stride intervals of the two participants within a pair. After a pair of participants performed the three conditions, they switched roles, had another habituation period in the new “leader/follower” configuration, and performed again the three conditions in random order.

Followers were instructed to synchronize their right heel strikes with leaders’ right heel strikes in the three conditions. Leaders were instructed to walk as naturally and as regularly as possible when no sound was audible in the earphones, and to synchronize the right heel strikes with the beat when sounds were administered. To accurately synchronize with the beats, leaders always ‘trampled’ for a few steps, so as to make followers believe that leaders were not self-paced. For standardization between the SP condition and the two others conditions, earphones displayed a dozens of regular beats and then vanished in the self-paced condition. Each condition in the second session lasted 6 min, to collect 256 stride intervals (Fig. 1), the minimum number necessary for an estimation of fractal exponents with the DFA [29]. Pierrynowski et al. [30] stressed that averaging the fractal exponents estimated in three repetitions of the same 6-min condition should provide a single accurate estimate of the fractal exponent characteristic of this condition. However, we could not live up to this advice due to the numerous different conditions in our experiment. Yet we are confident that the number
of participants should allow for a valid comparison of the mean fractal exponents between the different conditions.

2.4. Data processing

Stride-time series from leaders and followers were defined as the time intervals between two successive right heel strikes. Series of relative phase between follower and leader heel strikes (relative phase between participants, RP<sub>p</sub>) were calculated as:

\[
RP_p(i) = 360 \times \frac{F_{hs}(i) - L_{hs}(i)}{L_{hs}(i+1) - L_{hs}(i)}
\]

where \(i\) represents stride number, \(F_{hs}(i)\) and \(L_{hs}(i)\) refer to follower heel strike time and to leader heel strike time, respectively, for the \(i\)th stride. In IS0 and 1/f conditions, two more variables were analyzed: series of inter-onset intervals and series of relative phase between leader heel strikes and metronome onsets (relative phase with metronome, RP<sub>m</sub>), calculated as:

\[
RP_m(i) = 360 \times \frac{L_{hs}(i) - M_{hs}(i)}{M_{hs}(i+1) - M_{hs}(i)}
\]

where \(L_{hs}(i)\) and \(M_{hs}(i)\) refer to leader heel strike time and to metronome onset time, respectively, for the \(i\)th stride. The last points (excluding the last five points) of each time series were submitted to analysis.

To characterize the structure of correlations in stride-time series we used Detrended Fluctuations Analysis (DFA) [31]. DFA assesses the relationship between the magnitude of fluctuations of the variable and the duration over which these fluctuations are observed. Here the points of the diffusion plot were averaged so as to obtain 11 equidistant points, thereby avoiding possible biases in estimating \(\alpha\) due to their logarithmic distribution. \(\alpha\) then corresponded to the regression slope over these 11 points. The fractal exponent \(\alpha\) is of essential interest: a fully random series (white noise) corresponds to \(\alpha = 0.5\); time series containing anti-persistent correlations have \(\alpha < 0.5\), and persistent correlations imply \(\alpha > 0.5\). To examine the effect of the different metronome conditions (SP, ISO, and 1/f) and different roles (leader and follower) on the stride-time series structure, we applied a two-way (Condition \& Role) ANOVA with repeated measures on estimated \(\alpha\)'s. Tukey’s HSD was used for post hoc analysis. The results were deemed significant if \(p < 0.05\).

To assess the nature of adaptive processes occurring between followers and leaders, we performed a linear correlation analysis between \(\alpha_{\text{follower}}\) and \(\alpha_{\text{leader}}\). We expected a complexity matching [19,21] to occur to the long-range correlation structure of stride-time series of leaders. Hence, we performed separate correlation analyses on \(\alpha\) exponents obtained in the short-term and in the long-term regions of the diffusion plots: \(\alpha_{\text{short-term}}\) was given by the regression slope between the first point and the fourth point of the diffusion plot; \(\alpha_{\text{long-term}}\) was given by the regression slope between the last five points. This analysis allowed for evaluating the respective role of short-term and long-term adaptations in the scaling attenuation.

3. Results

Sixteen participants (8 males, 8 females; age: 27.0 ± 2.8 yrs, body height: 176.2 ± 12.1 cm, body mass: 69.8 ± 14.7 kg) yielded a difference between fractal exponents in Sessions 1a and 1b of less or equal to 0.1, and thus performed the second Session. Mean, standard deviation, and fractal exponent of stride intervals for these participants were not significantly different between Sessions 1a and 1b (Table 1). The mean absolute differences between mean
Table 1. Mean, standard deviation and fractal exponent of stride-time series in Sessions 1a and 1b, assessed over 16 participants (standard deviations in italics).

<table>
<thead>
<tr>
<th></th>
<th>Session 1a</th>
<th>Session 1b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (ms)</td>
<td>1125.45</td>
<td>1127.74</td>
</tr>
<tr>
<td>Standard deviation (ms)</td>
<td>68.12</td>
<td>67.23</td>
</tr>
<tr>
<td>Fractal exponent ($\alpha$)</td>
<td>2.81</td>
<td>2.54</td>
</tr>
<tr>
<td></td>
<td>0.81</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 2. Pearson correlation coefficient between $\alpha_{\text{leader}}$ and $\alpha_{\text{follower}}$, assessed over 16 participants.

<table>
<thead>
<tr>
<th></th>
<th>SP</th>
<th>1/f</th>
<th>ISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.75</td>
<td>0.72</td>
<td>0.85</td>
</tr>
<tr>
<td>$\alpha_{\text{short-term}}$</td>
<td>0.48</td>
<td>0.56</td>
<td>0.55</td>
</tr>
<tr>
<td>$\alpha_{\text{long-term}}$</td>
<td>0.81</td>
<td>0.92</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table 2. Pearson correlation coefficient between $\alpha_{\text{leader}}$ and $\alpha_{\text{follower}}$, assessed over 16 participants.

In this study we examined to what extent a human walker can influence the fractal exponent of stride time series of another human walker following stride. The relative phase close to 0° confirmed that followers effectively synchronized with leaders in all three conditions. Our results further indicated that the stride time series of the followers closely depended on those of the leaders. Across conditions we did not find any statistical difference between $\alpha$-leaders and $\alpha$-followers. The agreement between $\alpha_{\text{long-term}}$-exponents in all conditions implies that synchronization was mainly achieved by long-range processes and not primarily by local over-corrections.

Mean $\text{RP}_p$ indicated close to perfect synchronization (0°, Fig. 2) but also that followers slightly anticipated the heel strikes of the leaders [32]. The low variability of $\text{RP}_p$ indicated strong gait synchronization of followers to leaders [28]. This result confirmed that followers effectively synchronized with leaders, and that they did not react to the behavior but actively anticipated the occurrence of the steps. This anticipation is important because we could have expected that stride time series of followers matched those of leaders with a constant lag +1, if followers were only reacting to leaders. In this situation, $\alpha_{\text{follower}}$ and $\alpha_{\text{leader}}$ would have been the same, but only as a result of followers mimicking leaders.

Stride time series presented persistent fluctuations in SP and 1/f conditions. In contrast, anti-persistent fluctuations were present in ISO condition. The latter result is in accordance with the literature on sensori-motor synchronization with isochronous metronomes [12,15]. It is noteworthy that in the three conditions, $\alpha_{\text{follower}}$ was statistically similar to $\alpha_{\text{leader}}$. This result suggests that a human
partner may provide a simple, natural “metronome” for pacing gait. These results have to be confirmed in elderly populations, who typically exhibit lower fractal exponents, which might be increased through synchronization with another person’s gait. Increasing the fractal structure of stride time series is important: it could restore the optimal variability of strides, thus rendering the gait more adaptable to perturbations [16,17], or it could imply less stringent gait control, thus allowing the attention to focus on others parameters [14–18].

It is important to note that the present experiment was conducted on a treadmill: some studies have suggested that walking on a treadmill could decrease the fractal exponent of stride-time series compared to over-ground walking [6,18], but other studies did not find any differences [33,34]. Moreover, we were more interested in the matching of fractal exponents rather than on estimating its true value. Another limitation of the present study was the length of stride time series in the second session (256 stride intervals). This length represents the minimum to obtain reliable fractal exponents for a group [29]. Indeed, mean results between \( \alpha_3 \) (Session 1a), \( \alpha_{1b} \) (Session 1b) and \( \alpha_{lead} \) (SP condition, Session 2) were statistically similar, despite different time series length, and different recording days. However, one must stress that individual measures could be more controversial, in particular the correlations between fractal exponents. Further experiments with less but repeated conditions should establish the reliability of the present findings [30].

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