Fractal dynamics of human gait : a reassessment of Hausdorff et al. (1996)'s data.

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Abstract: Hausdorff et al. (1996) showed that the fractal properties of gait disappear during metronomic walking. A re-examination of their original data evidences that fractal processes are still present during metronomic walking: stride intervals present anti-persistent correlations, and long-range dependencies are detected in asynchronies. A modeling study showed that an auto-regressive correction process, based on the last asynchrony, allowed to simulate series possessing similar properties than those observed in empirical series. These results suggest that supra-spinal influences co-operate, but not compete, with correlated central pattern generators during metronomic walking.

Key words: Self-paced vs metronomic gait, fractal processes, auto-regressive correction

INTRODUCTION

Hausdorff, Peng, Ladin, Wei and Goldberger (1995) showed that successive step durations during self-paced walking presented a typical structure over time, characterized by the presence of (positive) long-range dependence, or fractal correlations. They also showed that when walking was paced by a metronome, this correlation structure disappeared and step duration evolved randomly over time, around the mean value imposed by the metronome. They suggested that supra-spinal influences could override the normally present long-range correlations.

The comparison between self-paced and paced cyclical behavior has also been studied in finger tapping (Chen, Ding, & Kelso, 1997). In that case, long-range correlations were also evidenced in inter-tap intervals produced in self-paced conditions. When tapping was paced by a metronome, correlation were still present in the inter-tap interval series, but became anti-persistent. In contrast, long-range correlations were observed in the series of asynchronies with the metronome. This pattern of results was successfully interpreted and modeled by the presence of an auto-regressive correction process, affecting the current inter-tap interval on the basis of the last asynchrony (Torre, Delignières & Lemoine, 2007).

The present study aimed at re-examining Hausdorff et al. (1996) data, in order to check whether a similar auto-corrective process could be at work in metronomic walking. A simulation study was also performed, on the basis of a model combining a correlated central pattern generator and a cognitive correction process.

EMPIRICAL SERIES

We analyzed the original series of Hausdorff et al. (1996)'s article, available at http://www.physionet.org/physiobank/database/umwdb/. These stride interval series were collected from 10 participants, in self-paced and paced conditions, and following slow, normal and fast speeds. On the basis of the series collected in paced conditions, we reconstructed the corresponding asynchronies series. We applied a set of time series analyses, including spectral analysis, Detrended Fluctuation analysis, R/S analysis, ARFIMA modeling and autocorrelation function.

Our results confirmed the presence of long-range dependence in stride interval series during self-paced walking, with Hurst exponents around 0.9. Contrary to Hausdorff et al. (1996), our

analyses evidenced the presence of anti-persistent correlations in the stride interval series collected in paced conditions, with Hurst exponents around 0.3. The analysis of asynchrony series revealed the presence of long-range dependence, with Hurst exponents around 0.8.

MODELING

These results paralleled those obtained in tapping experiments, and suggested that a similar auto-regressive correction process could be involved during metronomic walking. In order to test this hypothesis, we conducted a simulation study. The starting point was the 'hopping model' proposed by West and Scafetta (2003), which consists in a random walk performed on a correlated chain. This model is supposed to simulate the activity of a central pattern generator, and was shown to generate long-range dependence in the obtained series. This model was used for controlling discretely (cycle-by-cycle) the stiffness parameter of a hybrid limit cycle model (Kay, Saltzman, Kelso & Schöner, 1987). This first version of the model was used to simulate series of stride intervals in self-paced walking, and was shown to satisfactorily account for the Gaussian and fractal properties observed in empirical series.

In a second step, we introduced an auto-regressive correction process, correcting the actual stiffness parameter on the basis of the last asynchrony. This simple model allowed simulating stride intervals and asynchrony series, that presented similar Gaussian and fractal properties than those observed in empirical series.

DISCUSSION

These results suggest that the processes that underlie the presence of long-range dependence during paced walking are still at work during metronomic walking, and contradict the conclusions of Hausdorff et al. (1996), according to which supra-spinal influences could completely override the normally present long-range correlations in gait. The serial dependencies observed in series obtained in paced conditions can be explained by the combination of the influences of correlated central pattern generators, and of cognitive correction processes.

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