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Impact of series length on statistical precision and sensitivity of autocorrelation assessment in human locomotion

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ABSTRACT

Long-range autocorrelations (LRA) are a robust feature of rhythmic movements, which may provide important information about neural control and potentially constitute a powerful marker of dysfunction. A clear difficulty associated with the assessment of LRA is that it requires a large number of cycles to generate reliable results. Here we investigate how series length impacts the reliability of LRA assessment. A total of 94 time series extracted from walking or cycling tasks were re-assessed with series length varying from 64 to 512 data points. LRA were assessed using an approach combining the rescaled range analysis or the detrended fluctuation analysis (Hurst exponent, H), along with the shape of the power spectral density (α exponent). The statistical precision was defined as the ability to obtain estimates for H and α that are consistent with their theoretical relationship, irrespective of the series length. The sensitivity consisted of testing whether significant differences between experimental conditions found in the original studies when considering 512 data points persisted with shorter series. We also investigate the use of evenly-spaced diffusion plots as a methodological improvement of original version of methods for short series. Our results show that the reliable assessment of LRA requires 512 data points, or no shorter than 256 data points provided that more robust methods are considered such as the evenly-spaced algorithms. Such series can be reasonably obtained in clinical populations with moderate, or even more severe, gait impairments and open the perspective to extend the use of LRA assessment as a marker of gait stability applicable to a broad range of locomotor disorders.

1. Introduction

Temporal complexity is a hallmark of physiological systems, including the generation of rhythmic motor patterns such as gait or in the spontaneous activity of the heart (Peng, Havlin, Stanley, & Goldberger, 1995) or firing patterns of neurons (Bhattacharya, Edwards, Mamelak, & Schuman, 2005) under resting conditions. Indeed, recent studies have highlighted that most physiological signals continuously fluctuate over time in a complex manner, such that consecutive cycles exhibit an interdependency spanning over long time intervals (Bollens, Crevecoeur, Nguyen, Detrembleur, & Lejeune, 2010; Crevecoeur, Bollens, Detrembleur, & Lejeune, 2010; Delignieres et al., 2006; Goldberger et al., 2002; Peng et al., 1995; Stergiou & Decker, 2011).

Of particular interest is the potential use of long-range autocorrelations (LRA) to distinguish between healthy and pathological conditions in a number of diseases (Goldberger et al., 2002; Stergiou & Decker, 2011). In human locomotion, perturbations of LRA

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have been suggested as a marker of gait disorder and fall risk among patients with central nervous diseases such as Parkinson's disease, Huntington's disease, and amyotrophic lateral sclerosis (Hausdorff et al., 1997, 2000; Warlop et al., 2016).

One limitation of such approach is that physiological time series are unavoidably finite, whereas the presence of LRA is an asymptotic property, making the assessment of long-range dependency inherently based on approximations (Crevecoeur et al., 2010). Thus, it is crucial to determine a good balance between the series length, which in the context of clinical application is limited by patients' ability to perform a task for a long time, and the minimum number of cycles necessary to obtain a reliable assessment of the series autocorrelation function.

The issue of series length on its own has been considered previously. Although series of 512 data points have been usually considered in both synthetic (Delignieres et al., 2006) and physiological time series (Crevecoeur et al., 2010), methodological efforts are continuously made to improve the performance of the usual algorithms with even shorter series (Almurad & Delignières, 2016; Damouras, Chang, Sejdic, & Chau, 2010; Dingwell & Cusumano, 2010). Recently, the use of evenly spaced methods, which partially correct for the distortion of the data when transformed into logarithmic scale, yielded substantial improvement of the DFA with relatively short generated time series (i.e. 256 data points) (Almurad & Delignières, 2016). In human locomotion, such improvement could extend the LRA assessment to a broader range of locomotor disorders, especially for the most impaired patients for whom series of 512 cycles remain challenging to perform. We thus investigated the benefits of the evenly-spaced method on physiological series.

Given that the assessment of long-range correlations may provide an easy and effective tool to quantify gait stability (Hausdorff et al., 1997; Stergiou & Decker, 2011; Warlop et al., 2016), we investigated whether statistical precision and the sensitivity of the scaling parameters associated with the autocorrelation function could be preserved across series of shorter lengths. Our results suggest that reliable series as short as ~128 data points do not capture well the underlying scaling properties found in the same series when longer intervals are considered. Furthermore, we found that reliable results could be obtained with series no shorter than 256 data points, provided that robust techniques such as evenly-spaced regressions are used to mitigate the impact of the rather short series length. Gait stability assessment could be thus extended to population suffering from moderate or even more locomotor impairments, which are still able to perform a ~5 min continuous walking trial.

2. Materials and methods

2.1. Participants

We re-analysed the original time series (in walking or cycling conditions) collected from previous studies including a total of 47 healthy young adults (Bollens, Crevecoeur, Detrembleur, Warlop, & Lejeune, 2014; Warlop, Bollens, Crevecoeur, Detrembleur, & Lejeune, 2013). Their mean age was 23.2 (± 2.0) years, their mean weight was 69.2 (± 8.5) kg and their mean height was 178.3 (± 8.5) cm. Participants were free of any muscular, neurological, or orthopaedic pathology that could alter their locomotor performance. Each participant provided informed written consent and the procedures were approved by the local ethics committee at the host institution.

2.2. Procedure

Among the 47 participants, 32 were instructed to perform two different walking trials on a treadmill at their self-selected speed (Bollens et al., 2014): 20 were instructed to walk while performing or not a cognitive task (dual task or single task) and the 12 other participants were instructed to walk in backward and forward directions. The remaining 15 participants performed two cycling sessions on a friction-loaded cycle-ergometer at spontaneous and imposed (60 RPM) cadences (Warlop et al., 2013). Details on each protocol are provided in these original references. A total of 94 time series were re-evaluated in the present paper.

Data were recorded from the peak of the anteroposterior leg accelerations using a unidimensional accelerometer taped on the right malleolus for walking conditions and on the head of the right fibula for pedalling conditions (512 Hz). The extracted data were the stride or cycle duration for the gait or cycling conditions, respectively.

2.3. Reliability assessment of LRA estimates

The reliability of LRA estimates as a function of series length and algorithm used was assessed using statistical precision and sensitivity measures.

Statistical precision was defined as the ability to obtain similar LRA estimates, computed on original series of 512 data points, using a shorter series. In each condition (i.e., single and dual task, walking forward and backward, cycling at spontaneous and imposed cadence), mean exponent estimates (± SD) were calculated for the global number of participants for each series length and for both algorithms. To assess the statistical precision of the scaling exponent of interest, the standard deviation of those measures were calculated for each series length and algorithms. By highlighting a reduced standard deviation, a more precise estimate of the scaling exponent could be suggested.

Sensitivity was defined as the ability to reproduce the properties of the original series of 512 data points across testing conditions with varying series lengths and algorithms. Paired *t*-tests were used to verify whether conclusions edited from original comparisons persisted with shorter series.

To investigate the impacts of series length and of the algorithm considered on the assessment of LRA, each time series was re-analysed with various numbers of data points. Series length of 64, 128, 256 and 512 data points were considered. It should be noted