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Detection of co-regulation of local structure and magnitude of stride time variability using a new local detrended fluctuation analysis

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ABSTRACT

Detrended fluctuation analysis (DFA) is a popular method to numerically define the persistent structure of stride time variability. The conventional DFA assumes that the persistent structure in stride time variability is consistent in time and can be numerically defined by a single DFA scaling exponent. However, stride time regulation has to be adaptive to both environmental and internal perturbations and consequently, the persistent structure of stride time variability will have to be modulated in time. The present article introduces a new local detrended fluctuation analysis (DFA_{loc}) that is able to detect modulation in the structure of stride time variability generated by phase-couplings between temporal scales. DFA_{loc} was used in a reanalysis of the data set of stride time variability of Hausdorff et al. and a data set available at www.physionet.org. The results showed that there were significant phase couplings between temporal scales that generate an inverse correlation ($r = -0.54$ to -0.83) between the local structure and local magnitude of the stride time variability. Furthermore, the modulation of the local structure was significantly influenced by gait speed, external pace making, and age (all p's < 0.05). These results suggest several specific modifications of contemporary theories that have been suggested for the persistent structure of stride time variability found by the conventional DFA.

1. Introduction

The variability of spatiotemporal gait variables, like stride time, length, and width, can be numerically defined by both its magnitude and structure. Parameters of the magnitude, such as standard deviation and coefficient of variation, are the most common way to numerically define variability whereas parameters of structure, such as scaling exponents, have gained increased attention in several reports during the last decades [1–9]. Detrended fluctuation analysis (DFA) is one of the most common methods to numerically define the structure of variability in stride time, length, and speed [1–8]. The results from DFA indicate that stride time variability has a persistent structure but that the degree of persistency is dependent on multiple factors that are both internal and external to the nervous system.

Several studies have shown that the persistency in stride time variability declines with increased age and with the presence of neurodegenerative diseases such as Huntington and Parkinson's disease [2,5,6]. They further suggest that structural and functional degenerations in the central nervous system with age and diseases affect an internal pace-making mechanism of human gait [10,11]. In addition, the persistent structure of stride time variability has been shown to vanish when the cadence is set by an external metronome [1,12]. These findings further support that the persistent structure is generated by an internal pace-making mechanism within the central nervous system and that the decline in persistency reflects degeneration of the pace-making mechanism. According to this perspective, the decline in persistency of stride time variability has thus been interpreted as reflecting "unhealthy" gait function.

However, not all reports support the suggestion that the decline in persistency of stride time variability reflects an "unhealthy" gait function by degeneration of an internal pace-making mechanism. A U-shaped relationship between stride time persistency and gait speed has been found in several studies on both over-ground and treadmill walking [1,13]. The persistent structure of both stride time and length variability in treadmill walking reflected the stride-to-stride regulation of the gait speed to the treadmill, not an internal pace making mechanism [8]. Furthermore, peripheral neuropathy in diabetic patients did not change the persistent structure even though this pathological condition would have affected the sensor-motor integration within the central nervous system [7]. In addition, sensor-motor noise as external input to the

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central nervous system has been found to reproduce the persistent structure of stride time variability without the influence of an internal pace-making mechanism [14]. Thus, the persistent structure of stride time variability could reflect "healthy" stride time regulation to the walking condition rather than an "unhealthy" gait function. Consequently, it is still an unresolved issue how to interpret the results from DFA.

Common for all factors that affect the outcomes of DFA is their appearance in time. Motor errors and speed regulation appear as modulations of stride time variability over short time scales of milliseconds whereas aging and degeneration in the central nervous system appear as modulation of stride time variability over long time scales of years. Both kinds of modulations will yield temporal changes in the persistent structure of stride time variability. However, the conventional DFA assumes that the persistent structure is constant across strides and that the pace-making mechanism or sensor-motor noise are stationary mechanisms of stride time variability [11,14]. Results from analyses of both heart rate and stride time variability suggest that their persistent structures are temporally modulated. The temporal modulations of the structure in heart rate variability can distinguish between pathological conditions such as ventricular fibrillation and ventricular tachycardia, which cannot be distinguished in the outcomes of the conventional DFA [15]. Furthermore, the fluctuation in the structure of stride time variability is reported to be both age and speed dependent similar to the average structure defined by DFA [12,16]. Thus, the variation in the persistent structure of stride time variability, not only its average persistent structure, might be important to identify temporal changes in the stride time regulation.

The temporal modulations of the structure of variability are referred to as multifractal variations [17–20]. Multifractal variations have intermittent periods with a local decrease in the persistent structure of variability and intermittent periods with a local increase in the magnitudes of the variability. The intermittent coupling between the local structure and local magnitude of variability is generated by phase couplings between temporal scales. The main aim of the present study is to introduce a new local DFA (DFA_{loc}) of stride time variability that can identify variation in the persistent structure of stride time variability generated by phase couplings across temporal scales.

2. Methods

DFA_{loc} was used to reanalyze two data sets of [1] and [21]. Data set 1 contains stride time series of 60 min over-ground walking of slow (1.0 ± 0.1 m/s), preferred (1.4 ± 0.1 m/s) and fast (1.7 ± 0.1 m/s) gait speed for ten younger adults (age: 18–29 years, body mass: 71.8 ± 10.7 kg, height: 1.77 ± 0.08 m). The same trials were also conducted with an external cadence-setting metronome for 30 min over-ground walking. Data set 2 contains 15 min over-ground walking for five younger adults (age: 23–29 years) and five healthy older adults (age: 71–77 years). Further information for data sets 1 and 2 can be found in [1] and [21], respectively.

DFA_{loc} was conducted in the same way as the conventional DFA with three important differences. First, the root mean square of the detrended residuals was computed in a floating time interval across the integrated stride time series instead of in non-overlapping time intervals as in conventional DFA. The floating time intervals had a length n, referred to as the scale, and were centered at time t. Secondly, the obtained root-mean-square measure $F(n,t)$ was dependent on both time and scale in contrast to the root-mean-square measure $F(n)$ of the conventional DFA that is only dependent on scale (i.e., average of $F(n,t)$ across time t). Thirdly, a local DFA scaling exponent $\alpha(t)$ is numerically defined by the linear slope of $\log[F(n,t)]$ versus $\log(n)$ for each time instant t instead of by the time-independent $\log[F(n)]$ versus $\log(n)$ for the conventional DFA. A modified procedure developed by [22] was

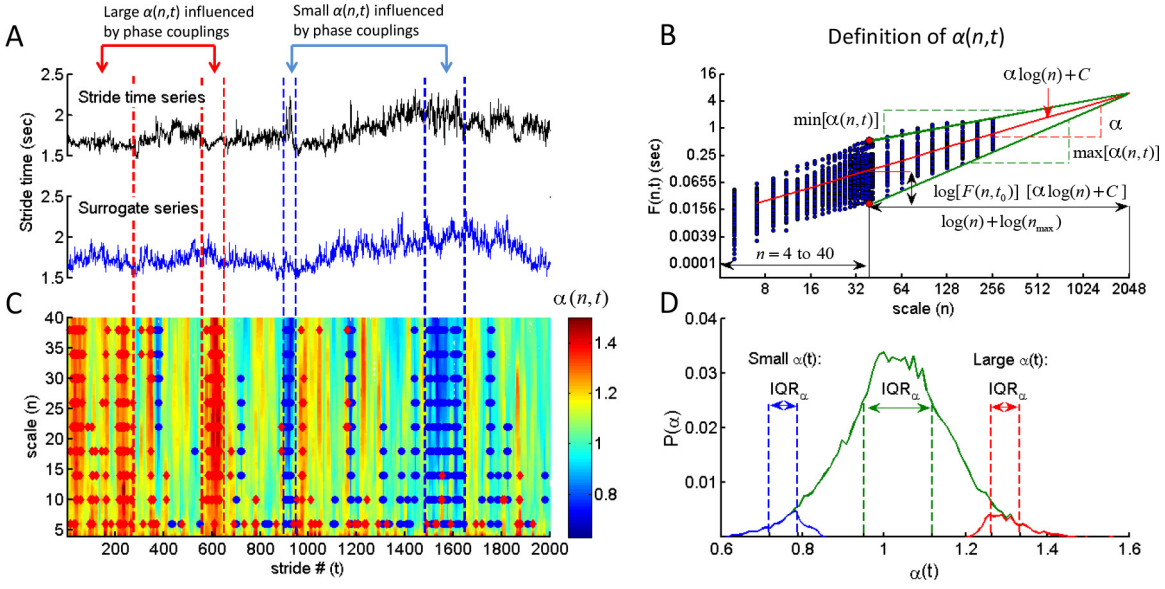

Fig. 1. Illustration of DFA_{loc} and the corresponding Monte Carlo surrogate test for stride time variability. Panel A: A stride time series (black trace) and a surrogate time series (blue trace) where the phase couplings between temporal scales are removed. Panel B: The definition of DFA_{loc} scaling exponents $\alpha(n,t)$ of stride time series and surrogate series. The root-mean-square variation $F(n,t)$ is plotted for each scale n (in log–log coordinates) and stride number t (cluster of blue dots). The DFA_{loc} scaling exponent $\alpha(n,t)$ is defined as the difference between $\log[F(n,t)]$ and the regression line $\alpha\log(n) + C$ (vertical black arrows) of the conventional DFA (red line) for each stride t divided by the difference between the scale n = 4 to 40 of $F(n,t)$ and the maximum scale n_{max} (horizontal black arrows). The slope of the green lines are $\max[\alpha(n,t)]$ and $\min[\alpha(n,t)]$. Panel C: Contour plot of $\alpha(n,t)$ resolved in stride number t and scale n resolution where the red contours indicate intermittent periods of more persistent variation (i.e., large $\alpha(n,t)$) and blue contours indicate intermittent periods of less persistent variation (i.e., small $\alpha(n,t)$). The red diamonds and blue circles indicate the stride number and scale where the large and small $\alpha(n,t)$, respectively, are significantly influenced by phase couplings ($p < 0.025$). Panel D: The probability distribution $p(\alpha)$ of all DFA_{loc} scaling exponents $\alpha(n,t)$ (green trace), and large $\alpha(n,t)$ (red trace) and small $\alpha(n,t)$ (blue trace) influenced by phase couplings. The green, red and blue intervals indicate the width of distributions $p(\alpha)$ numerically defined as interquartile ranges (IQR_α). (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)