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Short communication

The effect of walking speed on local dynamic stability is sensitive to calculation methods

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ABSTRACT

Local dynamic stability has been assessed by the short-term local divergence exponent (λ_S), which quantifies the average rate of logarithmic divergence of infinitesimally close trajectories in state space. Both increased and decreased local dynamic stability at faster walking speeds have been reported. This might pertain to methodological differences in calculating λ_S. Therefore, the aim was to test if different calculation methods would induce different effects of walking speed on local dynamic stability. Ten young healthy participants walked on a treadmill at five speeds (60%, 80%, 100%, 120% and 140% of preferred walking speed) for 3 min each, while upper body accelerations in three directions were sampled. From these time-series, λ_S was calculated by three different methods using: (**a**) a fixed time interval and expressed as logarithmic divergence per stride-time ($\lambda_{S-\mathbf{a}}$), (**b**) a fixed number of strides and expressed as logarithmic divergence per time ($\lambda_{S-\mathbf{b}}$) and (**c**) a fixed number of strides and expressed as logarithmic divergence per stride-time ($\lambda_{S-\mathbf{c}}$). Mean preferred walking speed was 1.16 ± 0.09 m/s. There was only a minor effect of walking speed on $\lambda_{S-\mathbf{a}}$. $\lambda_{S-\mathbf{b}}$ increased with increasing walking speed indicating decreased local dynamic stability at faster walking speeds, whereas $\lambda_{S-\mathbf{c}}$ decreased with increasing walking speed indicating increased local dynamic stability at faster walking speeds. Thus, the effect of walking speed on calculated local dynamic stability was significantly different between methods used to calculate local dynamic stability. Therefore, inferences and comparisons of studies employing λ_S should be made with careful consideration of the calculation method.

1. Introduction

Local dynamic stability, quantified using local divergence exponents, is a promising measure of gait stability (Bruijn et al., 2013). Local divergence exponents quantify the average rate of logarithmic divergence of infinitesimally close trajectories in state space (Rosenstein et al., 1993) and is suggested to reflect the ability to attenuate the small perturbations that occur naturally during gait (van Schooten et al., 2014). A locally stable system is characterized by a negative local divergence exponent, whereas a locally unstable system is characterized by a positive exponent (Dingwell, 2006). Larger exponents indicate a more locally unstable system because of a more rapid expansion of the system's principal axis. Growing evidence from both simulation and experimental studies suggests that the short-term local divergence exponent, λ_S, that quantifies the system's response over a shorter time period may be related to stability impairments, the probability of falling in models and as an index for rehabilitation effect on fall risk (Manor et al., 2009; McAndrew et al., 2011; Roos and Dingwell, 2011; van Schooten et al., 2011; Bruijn et al., 2012; Hilfiker et al., 2013).

Reported effects of walking speed on local dynamic stability have been inconclusive (Dingwell and Marin, 2006; England and Granata, 2007; Kang and Dingwell, 2008; Manor et al., 2008; Bruijn et al., 2009a, 2010; Yakhdani et al., 2010). For example, Dingwell and Marin (2006) and England and Granata (2007) found decreased local dynamic stability, i.e. higher λ_S, with faster walking, while Bruijn et al. (2009a) found different effects of walking speed on the movement directions studied. This might pertain to methodological differences in calculating λ_S. Specifically, Dingwell and Marin (2006) analyzed a fixed time interval for all walking speeds. This implies that more strides will be analyzed at faster walking speeds, which might affect λ_S (Bruijn et al., 2009b). In order to overcome this potential bias England and Granata (2007) analyzed a fixed number of strides for all speeds and time-normalized each time-series to 100 points per analyzed stride. However, instead of expressing λ_S as logarithmic

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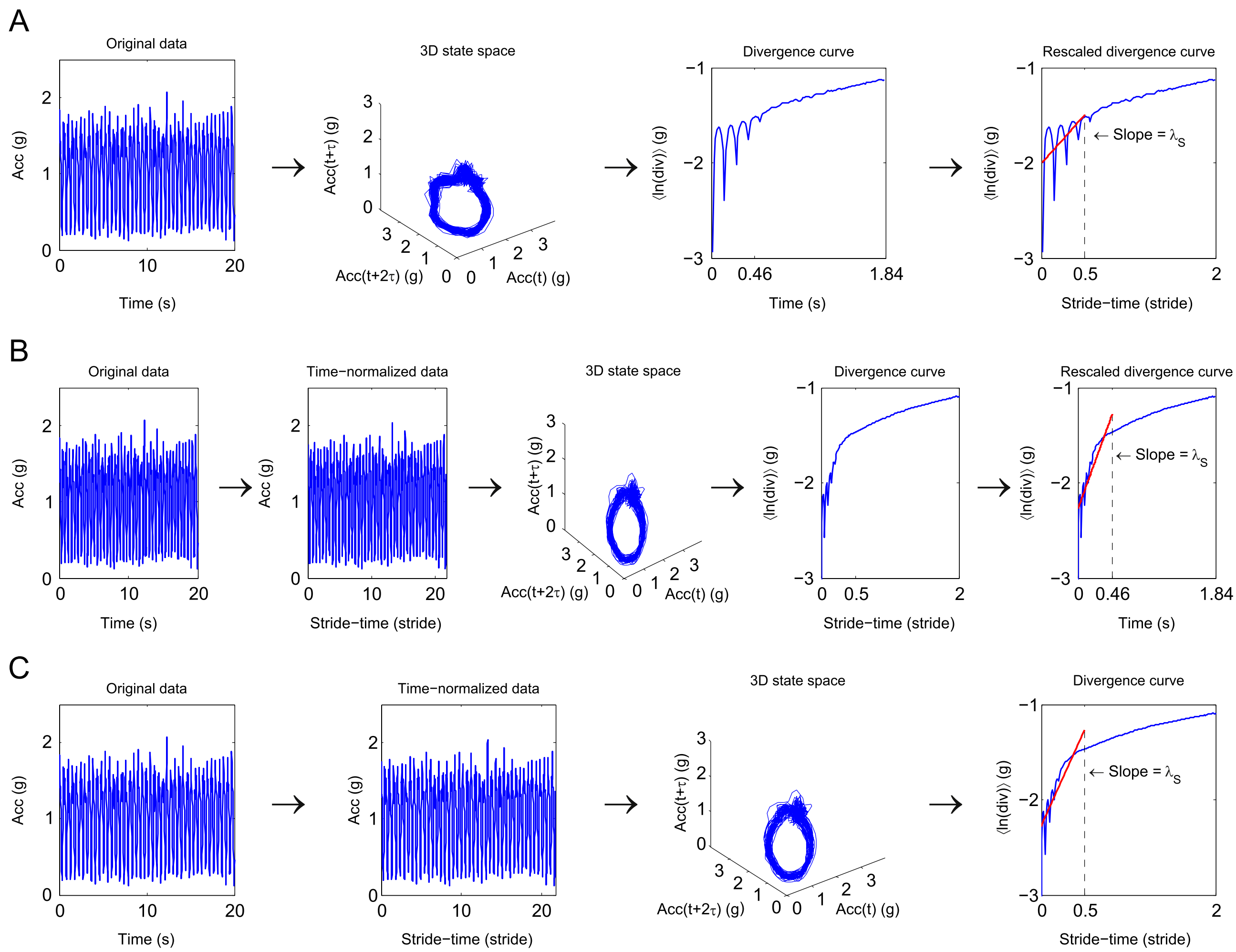

Fig. 1. Schematic representation of short-term local divergence exponent (λ_S) calculation methods **a**, **b** and **c**, each quantifying local dynamic stability. Method **a** reconstructed state spaces from the original 3 min acceleration time-series for each walking speed and acceleration direction; normalized the temporal separation between data points to a percentage of the time it takes to complete a stride (stride-time); and expressed λ_S as mean logarithmic divergence of nearest neighbors in state space (⟨ln(div)⟩)/stride-time from 0–0.5 stride, i.e. λ_S has the unit g/stride (A). Method **b** reconstructed state spaces from time-normalized acceleration time-series for the first 115 strides for each walking speed and direction; normalized the temporal separation between data points to time in seconds; and expressed λ_S as ⟨ln(div)⟩/time from 0–0.5 stride, i.e. λ_S has the unit g/s (B). Method **c** reconstructed state spaces from time-normalized acceleration time-series for the first 115 strides for each walking speed and direction; and expressed λ_S as ⟨ln(div)⟩/stride-time from 0–0.5 stride, i.e. λ_S has the unit g/stride (C). Only accelerations for 20 s are shown and state spaces are reconstructed in 3 dimensions for graphical representation (stride duration = 0.92 s).

divergence (ln(div)) per stride-time, they expressed it as ln(div) per time in seconds (England and Granata, 2007; Fig. 3), which introduced a dependency upon stride duration. Manor et al. (2008), analyzing a fixed number of strides for all speeds and expressing λ_S as ln(div) per stride-time, found decreased local dynamic stability at faster speeds for people with peripheral neuropathy, however, for healthy controls there was no effect of walking speeds on local dynamic stability. Presently, we hypothesized that analyzing a fixed time interval or a fixed number of strides for all walking speeds and expressing λ_S as ln(div) per stride-time or ln(div) per time, constituted important methodological differences in calculating λ_S that could induce different effects of walking speed on λ_S. The aim of the present study was to test if these methodological differences in calculating λ_S would induce different effects of walking speed on this measure.

2. Methods

2.1. Participants

10 healthy young participants were recruited (6 men and 4 women, (mean ± SD): age 22.6 ± 2.8 years, body mass 70.6 ± 6.5 kg, body height 1.78 ± 0.08 m). Participants gave informed written consent before participation. The study was registered by the regional ethics committee (H-1-2014-FSP-006).

2.2. Procedure

Participants reported to the laboratory on two non-consecutive test days, with 1 to 8 weeks between test days (3.5 ± 3.0 weeks). On the first test day, preferred walking speed (PWS) was determined prior to testing on a treadmill. PWS was calculated using the method by Dingwell and Marin (2006). On both test days, participants walked for 3 min at 60%, 80%, 100%, 120% and 140% PWS, in random order, on a treadmill, with 1 min rest between trials. An accelerometer (range ± 6 g, Marq-Medical, Copenhagen, Denmark) was mounted on the sternum. Accelerations in vertical (VT), medio-lateral (ML) and antero-posterior (AP) directions were sampled at 64 Hz (Bluetooth connection) when the treadmill reached a constant speed.

2.3. Calculations

2.3.1. Pre-processing

Time-series were not filtered before further analysis (Mees and Judd, 1993). The first 115 strides for each time-series, determined from the VT acceleration, were identified.

2.3.2. Local dynamic stability

State spaces were reconstructed from each acceleration direction using the method of delays (Takens, 1981):

$$S(t) = [x(t),\ x(t+\tau),\ \ldots,\ x(t+\tau(d_E-1))],$$