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Complexity, fractal dynamics and determinism in treadmill ambulation: Implications for clinical biomechanists

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ABSTRACT

Background: Reduced inter-stride complexity during ambulation may represent a pathologic state. Evidence is emerging that treadmill training for rehabilitative purposes may constrain the locomotor system and alter gait dynamics in a way that mimics pathological states. The purpose of this study was to examine the dynamical system components of gait complexity, fractal dynamics and determinism during treadmill ambulation.
Methods: Twenty healthy participants aged 23.8 (1.2) years walked at preferred walking speeds for 6 min on a motorized treadmill and overground while wearing APDM 6 Opal inertial monitors. Stride times, stride lengths and peak sagittal plane trunk velocities were measured. Mean values and estimates of complexity, fractal dynamics and determinism were calculated for each parameter. Data were compared between overground and treadmill walking conditions.
Findings: Mean values for each gait parameter were statistically equivalent between overground and treadmill ambulation ($P > 0.05$). Through nonlinear analyses, however, we found that complexity in stride time signals ($P < 0.001$), and long-range correlations in stride time and stride length signals ($P = 0.005$ and $P = 0.024$, respectively), were reduced on the treadmill.
Interpretation: Treadmill ambulation induces more predictable inter-stride time dynamics and constrains fluctuations in stride times and stride lengths, which may alter feedback from destabilizing perturbations normally experienced by the locomotor control system during overground ambulation. Treadmill ambulation, therefore, may provide less opportunity for experiencing the adaptability necessary to successfully ambulate overground. Investigators and clinicians should be aware that treadmill ambulation will alter dynamic gait characteristics.

1. Introduction

Gait must be adequately rhythmic and stable to prevent falls yet sufficiently adaptable to accommodate destabilizing demands. Attaining both stability and adaptability poses challenges to bipedal ambulation. An implication of those challenges is that some inter-stride variability may represent a healthy state of being. Supporting the concept that some variability in recurring gait cycles is healthy, there is evidence in physiological systems that loss of complexity represents a pathological state (Lipsitz and Goldberger, 1992). While gait patterns are cyclical and typically characterized by low variability in healthy adults (Hollman et al., 2007), evidence suggests that consecutive strides are correlated over wide ranges of time scales (Hausdorff et al., 1995) and that apparent random fluctuations in stride intervals are not random but instead chaotic and statistically distinct from Gaussian noise (Dingwell and Cusumano, 2000). Furthermore, consistent with the hypothesis that reduced complexity indicates pathological states (Lipsitz and Goldberger, 1992), evidence has emerged that reduced signal complexity in stride length and step width parameters distinguish people with neurological conditions from healthy controls (Hausdorff et al., 1998; Kaipust et al., 2012).

Human gait represents a dynamical process, meaning that its properties exhibit change over time (Richardson and Chemero, 2014). In dynamical systems, traditional linear methods of quantification—such as means and standard deviations—may not be particularly informative because they do not account for how the measures vary at different time frames. Measuring dynamical systems therefore requires nonlinear mathematical tools to capture the dynamics being exhibited. Three properties that characterize dynamical systems are complexity, self-similarity and determinism. First, complex systems are characterized by self-organized behaviors that emerge from nonlinear interactions across multiple components (Richardson and Chemero, 2014). Complexity in physiological systems is characterized by chaotic signals that vary in erratic and unpredictable manners, as illustrated in Fig. 1A. Complex systems generate new, non-redundant information over time whereas non-complex, recurrent systems generate less new

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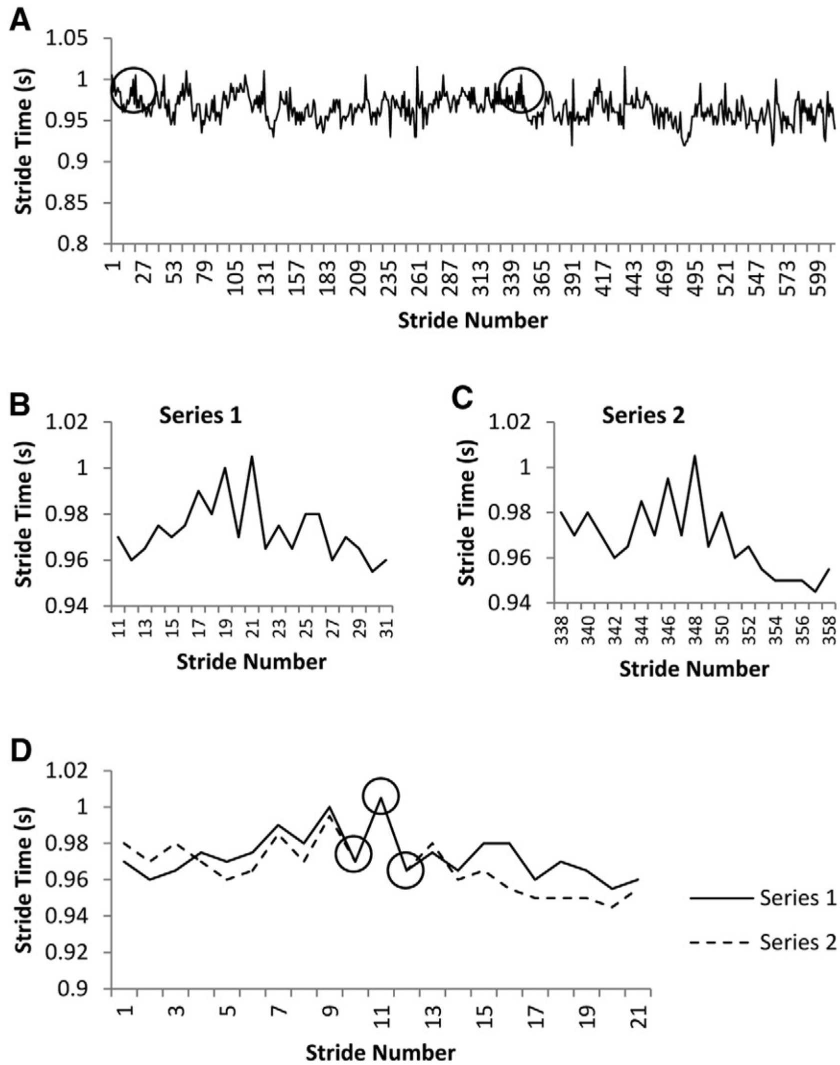

Fig. 1. Representative data partially illustrating the processes by which sample entropy is determined. The output signal—a trial series of successive stride time data from a participant during overground walking—illustrates a complex signal with fluctuating data that vary chaotically over repeated strides (A). Data encompassing approximately 20 strides around the participant's 21st (series 1) and 348th strides (series 2) in the trial series, respectively, are presented (B and C). An overlay plot of the series 1 and series 2 stride time data illustrates repeating 3-point vectors in the trial series data (D). Trial series with lower proportions of repeating vectors have higher sample entropy values, or greater complexity in the signal.

information over time. A system's complexity may be quantified by *entropy*, which refers to magnitudes of disorder in thermodynamics and rates of information generation in information theory (Shannon, 1948). Second, many physiological systems exhibit fractal characteristics, meaning that patterns of change over time exhibit self-similar properties in which signal fluctuations at shorter measurement scales mimic those at longer measurement scales (Goldberger et al., 2002). Self-similar characteristics in physiological systems with fractal-like properties can be quantified with long-range correlations in trial series data through adaptive fractal analysis (AFA). Third, determinism in physiological systems represents the extent to which a system's state is governed by some "rule" that fixes past states to future states (Zbilut, 2003). Determinism can be quantified through recurrence quantification analysis (RQA). Studies have demonstrated that nonlinear measurements characterizing inter-stride fluctuations in gait enumerate properties of locomotor control that are fundamentally distinct from those determined by linear measures of variability such as standard deviations or coefficients of variation (Dingwell et al., 2001; Terrier and Deriaz, 2011).

Many strides are required to analyze nonlinear gait dynamics, therefore treadmills may be used as a surrogate for overground walking (England and Granata, 2007). Motorized treadmills offer advantages of reduced space requirements, ease of capturing data from many strides and controlled walking speed. Additionally, they may offer rehabilitative advantages in persons with gait deficits (Bello et al., 2013; Langhammer and Stanghelle, 2010). Treadmills, however, induce less variant gait patterns (Hollman et al., 2016) and may alter locomotor control strategies that impact one's ability to translate locomotor skills to overground walking conditions (Combs-Miller et al., 2014). While we and others have compared multiple linear measures of spatiotemporal gait parameters between overground and treadmill ambulation, with equivocal results (Alton et al., 1998; Hollman et al., 2016; Murray et al., 1985), only two studies to our knowledge have compared nonlinear dynamics of treadmill ambulation to overground ambulation. Dingwell et al. (Dingwell et al., 2001) and Terrier & Dériaz (Terrier and Deriaz, 2011) reported that treadmill ambulation reduced short- and long-term maximum Lyapunov exponents of lower extremity kinematics and trunk accelerations, representing increased local stability during treadmill ambulation. Terrier & Dériaz (Terrier and Deriaz, 2011) additionally reported that treadmill ambulation reduced fractal-like long-range correlations in stride time signals. Other nonlinear measures of inter-stride dynamics such as complexity and determinism during treadmill ambulation have not been reported. The purpose of this study was to examine whether those dynamical characteristics would