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Association between stride time fractality and gait adaptability during unperturbed and asymmetric walking

Scott W. Ducharme[a,b,*], Joshua J. Liddy[c], Jeffrey M. Haddad[c], Michael A. Busa[d], Laura J. Claxton[c], Richard E.A. van Emmerik[a]

[a] Motor Control Laboratory, University of Massachusetts-Amherst, Amherst, MA, USA
[b] Physical Activity & Health Laboratory, University of Massachusetts-Amherst, Amherst, MA, USA
[c] Motor Development and Control Laboratory, Purdue University, West Lafayette, IN, USA
[d] Institute for Applied Life Sciences, University of Massachusetts-Amherst, Amherst, MA, USA

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ABSTRACT

Human locomotion is an inherently complex activity that requires the coordination and control of neurophysiological and biomechanical degrees of freedom across various spatiotemporal scales. Locomotor patterns must constantly be altered in the face of changing environmental or task demands, such as heterogeneous terrains or obstacles. Variability in stride times occurring at short time scales (e.g., 5–10 strides) is statistically correlated to larger fluctuations occurring over longer time scales (e.g., 50–100 strides). This relationship, known as fractal dynamics, is thought to represent the adaptive capacity of the locomotor system. However, this has not been tested empirically. Thus, the purpose of this study was to determine if stride time fractality during steady state walking associated with the ability of individuals to adapt their gait patterns when locomotor speed and symmetry are altered. Fifteen healthy adults walked on a split-belt treadmill at preferred speed, half of preferred speed, and with one leg at preferred speed and the other at half speed (2:1 ratio asymmetric walking). The asymmetric belt speed condition induced gait asymmetries that required adaptation of locomotor patterns. The slow speed manipulation was chosen in order to determine the impact of gait speed on stride time fractal dynamics. Detrended fluctuation analysis was used to quantify the correlation structure, i.e., fractality, of stride times. Cross-correlation analysis was used to measure the deviation from intended anti-phasing between legs as a measure of gait adaptation. Results revealed no association between unperturbed walking fractal dynamics and gait adaptability performance. However, there was a quadratic relationship between perturbed, asymmetric walking fractal dynamics and adaptive performance during split-belt walking, whereby individuals who exhibited fractal scaling exponents that deviated from 1/f performed the poorest. Compared to steady state preferred walking speed, fractal dynamics increased closer to 1/f when participants were exposed to asymmetric walking. These findings suggest there may not be a relationship between unperturbed preferred or slow speed walking fractal dynamics and gait adaptability. However, the emergent relationship between asymmetric walking fractal dynamics and limb phase adaptation may represent a functional reorganization of the locomotor system (i.e., improved interactivity between degrees of freedom

* Corresponding author at: Physical Activity & Health Laboratory, 162 Totman Building, 30 Eastman Lane, University of Massachusetts, Amherst, Amherst, MA 01003, USA.

E-mail addresses: sducharm@umass.edu (S.W. Ducharme), jliddy@purdue.edu (J.J. Liddy), jmhaddad@purdue.edu (J.M. Haddad), mbusa@umass.edu (M.A. Busa), ljclaxton@purdue.edu (L.J. Claxton), rvanemmerik@kin.umass.edu (R.E.A. van Emmerik).

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within the system) to be better suited to attenuate externally generated perturbations at various spatiotemporal scales.

1. Introduction

Human locomotion is an inherently complex activity that requires the control and coordination of many neurophysiological and biomechanical degrees of freedom. Successful locomotion therefore demands the integration of various physiological systems that are organized hierarchically across different spatiotemporal scales. For example, achieving a single step requires that the motor units innervating the muscles crossing a joint activate in a coordinated fashion to generate the appropriate joint torques. At larger scales, inter-limb dynamics may be controlled by higher order centers (e.g., areas within the motor cortex). At smaller scales, muscular force production requires the modulation of the dynamic interaction between calcium and filament components (e.g., actin, myosin) at the level of a single sarcomere. Thus, successful locomotion requires the integration of sensorimotor processes across various spatiotemporal scales to attenuate potential disturbances. From a system's perspective, gait adaptability and stability emerge from the interactions among these processes (Goldberger, 1996; Ivanov et al., 2009; Manor & Lipsitz, 2013). Gait adaptability refers to the capacity to alter locomotor patterns in response to changing environmental or task demands (Balasubramanian, Clark, & Fox, 2014).

Biological systems inherently exhibit variable behavior. Understanding the nature of these fluctuations can provide important information about the system. For example, gait parameter variability has consistently been associated with fall risk, whereby higher variability has been linked to reduced stability and system control, particularly in older adults (Dean, Alexander, & Kuo, 2007; Hausdorff, 2005; Maki, 1997; Owings & Grabiner, 2004). However, the magnitude of variability only provides one dimension of information about the locomotor system. Alternatively, the temporal *structure* of variability has been postulated to represent a measure of walking adaptability (Hausdorff, Peng, Ladin, Wei, & Goldberger, 1995; Hausdorff et al., 1996; Lipsitz & Goldberger, 1992; Peng, Havlin, Stanley, & Goldberger, 1995).

There is substantial evidence demonstrating that the temporal structure of gait variability is not random, as previously believed, but rather exhibits statistically persistent, long-range correlated fluctuations (Bollens, Crevecoeur, Nguyen, Detrembleur, & Lejeune, 2010; Hausdorff, 2007; Hausdorff, Zemany, Peng, & Goldberger, 1999; Hausdorff et al., 1995, 1996, 1997; Ihlen & Vereijken, 2014; Jordan, Challis, & Newell, 2007; Marmelat, Torre, Beek, & Daffertshofer, 2014; Rhea & Kiefer, 2014; Terrier & Deriaz, 2011, 2012). Long-range correlated processes exhibit multiscale dependence on previous behavioral states and lack a characteristic timescale. Statistically persistent processes are positively correlated such that successive deviations are statistically more likely to occur in the same direction. For example, long or short stride times are likely to be followed by more long or short stride times, respectively. These biological processes are often referred to 'fractal' based on their characteristic scale invariant nature.

Scale invariance indicates structural or behavioral complexity, and is a hallmark of healthy, adaptable systems (Lipsitz, 2002). If the power of the signal is dispersed (i.e., not concentrated at any portion of the frequency domain) in a manner that allow perturbations at any given scale to be attenuated, the system may be considered more adaptable (Delignieres et al., 2006). Thus, the fractal properties observed in walking appear to represent dynamics of an adaptive system because the presence of long-term correlations may indicate interactivity among biological processes that help to attenuate perturbations (Delignieres & Marmelat, 2012; Delignieres et al., 2006; Rhea & Kiefer, 2014; Stergiou & Decker, 2011). Fractal gait dynamics have been reported to decrease in healthy older adults (Hausdorff et al., 1997) and those with neurological disorders, such as Parkinson's (Hausdorff, 2009) and Huntington's (Hausdorff et al., 1997) disease. Moreover, older adults with a history of falls display reduced fractal scaling compared to healthy older adults (Herman, Giladi, Gurevich, & Hausdorff, 2005). These observations provide further evidence for a connection between fractal dynamics and locomotor adaptive capabilities. However, this potential relationship has not yet been examined empirically.

Experimentally, gait adaptability can be tested in various ways, and it is generally evaluated by evoking task or environmental constraints, thereby requiring individuals to alter locomotor patterns in order to successfully continuing walking. Among these many experimental designs, a common paradigm that assesses long-term locomotor adaptations is by inducing limb asymmetry with a split-belt treadmill (Bruijn, Van Impe, Duysens, & Swinnen, 2012; Choi & Bastian, 2007; Choi, Vining, Reisman, & Bastian, 2009; Dietz, Zijlstra, & Duysens, 1994). This treadmill has separate belts whose speeds can be independently controlled, allowing for exposure to chronic asymmetric walking patterns by driving the two limbs at different speeds. The noteworthy advantage to this paradigm is that individuals are exposed to a novel walking task, and researchers can quantify how (and at what rate) the individuals adapt. Generally, participants initially respond to the differential belt speeds by exhibiting asymmetric locomotor patterns, and over time shift towards greater symmetry of various patterns, such as leg relative phasing (Choi & Bastian, 2007), step length (Bruijn et al., 2012), or stance and swing time (Dietz et al., 1994). The initial degree of leg asymmetry, as well as the rate at which individuals regain symmetry, are measures of gait adaptation.

Fractal dynamics are thought to represent the adaptive capacity of the locomotor system. The asymmetric walking paradigm offers the opportunity to evaluate locomotor adaptations to a novel walking perturbation and their relation to fractal dynamics. Moreover, while organismic (e.g., age and disease) and task-level (e.g., gait speed (Hausdorff et al., 1996; Jordan et al., 2007)) constraints alter fractal dynamics, it is unclear how asymmetric walking might affect fractality. Thus, the purpose of this study was to determine if stride time fractality during unperturbed and asymmetric walking in young, healthy adults predicts an individual's ability to successfully and quickly adapt locomotor patterns when exposed to gait asymmetries. We exposed participants to