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Entrainment to a real time fractal visual stimulus modulates fractal gait dynamics

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A B S T R A C T

Fractal patterns characterize healthy biological systems and are considered to reflect the ability of the system to adapt to varying environmental conditions. Previous research has shown that fractal patterns in gait are altered following natural aging or disease, and this has potential negative consequences for gait adaptability that can lead to increased risk of injury. However, the flexibility of a healthy neurological system to exhibit different fractal patterns in gait has yet to be explored, and this is a necessary step toward understanding human locomotor control. Fifteen participants walked for 15 min on a treadmill, either in the absence of a visual stimulus or while they attempted to couple the timing of their gait with a visual metronome that exhibited a persistent fractal pattern (contained long-range correlations) or a random pattern (contained no long-range correlations). The stride-to-stride intervals of the participants were recorded via analog foot pressure switches and submitted to detrended fluctuation analysis (DFA) to determine if the fractal patterns during the visual metronome conditions differed from the baseline (no metronome) condition. DFA α in the baseline condition was 0.77 ± 0.09. The fractal patterns in the stride-to-stride intervals were significantly altered when walking to the fractal metronome (DFA $\alpha = 0.87 \pm 0.06$) and

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to the random metronome (DFA $\alpha = 0.61 \pm 0.10$) (both $p < .05$ when compared to the baseline condition), indicating that a global change in gait dynamics was observed. A variety of strategies were identified at the local level with a cross-correlation analysis, indicating that local behavior did not account for the consistent global changes. Collectively, the results show that a gait dynamics can be shifted in a prescribed manner using a visual stimulus and the shift appears to be a global phenomenon.

1. Introduction

Healthy individuals produce temporal gait patterns, or rhythms, that are not consistent from stride to stride. Rather, each stride interval varies slightly due to the complex nature of locomotor control. These patterns not only reflect the coordination of many neuro-musculo-skeletal components to generate a fluid walking motion, but also reflect sensorimotor modulation by proprioceptive and visual information (Glass, 2001). Together they lead to variability in the stride-to-stride rhythm. The magnitude of the variability was once used as a marker of locomotor dysfunction. Specifically, greater variability was believed to be caused by imprecise locomotor control. However, further examination of the structure of the stride-to-stride variability has revealed that patterns emerge that exhibit self-similarity—termed a fractal pattern—at many different temporal scales (Hausdorff, 2007; Hausdorff, Peng, Ladin, Wei, & Goldberger, 1995): a characteristic that is shared by living systems at many levels, including cardiac and respiratory rhythms as well as neural firing patterns (Glass, 2001; West, 2006). Many names have been used to describe this structure, including persistence, long-range correlations, $1/f$ scaling and pink noise. For consistency in this paper, we will use the term fractal when talking about self-similarity in general and the terms persistence (structured temporal fluctuations) and randomness (unstructured temporal fluctuations) to describe the nature of gait variability.

Fractal patterns in biological rhythms may reflect the underlying control processes that govern the system. For example, a change in the structure of physiological rhythms has been observed in disease and aging, suggesting that persistence in the variability patterns may reflect healthy functioning in biological systems (Van Orden, 2007; West, 2006). This is true of the stride-to-stride variability in gait as well (Bartsch et al., 2007; Choi et al., 2011; Hausdorff, Zemany, Peng, & Goldberger, 1999; Hausdorff et al., 1997; Lamoth et al., 2011). For example, Hausdorff and his colleagues have demonstrated a systematic shift from persistence toward randomness in the stride intervals of patients suffering from Huntington's disease—a neurodegenerative disease affecting the central nervous system—as well as in aging gait (Hausdorff et al., 1997). Conversely, persistence is preserved in patients suffering from peripheral neuropathy (Gates & Dingwell, 2007)—a disease affecting the peripheral nervous system—and also in patients known to exhibit neuromuscular and proprioceptive deficits following an anterior-cruciate ligament injury (Rhea, Kiefer, D'Andrea, Warren, & Aaron, 2010).

A breakdown in the temporal structure of stride intervals has also been shown to occur when individuals synchronize their strides with a standard auditory metronome (Hausdorff et al., 1996), and this result has been replicated during the synchronization of finger taps to a metronome (Chen, Ding, & Kelso, 1997). It has been suggested that the metronome constrains the locomotor system by overriding the normal control processes that produce the gait rhythm, and that this ultimately leads to a breakdown in the temporal structure of stride intervals (Hausdorff et al., 1996). However, it should be noted that there is a lack of consensus about the nature of the observed changes in the temporal structure (Delignières & Torre, 2009).