

PERIPHERAL SENSORY FEEDBACK AFFECTS LOCOMOTOR ‘COMPLEXITY’

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INTRODUCTION

It has been argued that peripheral sensory feedback is “essential” for maintaining stable bipedal locomotion (Winter 1983). However, completely passive walking machines that exhibit stable locomotion (McGeer 1993) call this assumption into question. Patients with diabetic neuropathy provide a unique model for studying the role of peripheral feedback in locomotor control.

Nonlinear and chaotic behavior of analytical models of locomotor systems (Collins and Stewart 1993; Goswami et al. 1998) demonstrate that linear analyses can not fully characterize locomotor complexity. The present study used methods from nonlinear time series analysis to provide a mathematically rigorous means of quantifying the structural complexity of locomotor kinematics.

METHODS

Fourteen diabetic patients with significant peripheral neuropathy (NP) and 12 appropriately matched controls (CO) participated. Upper-body 3D accelerations and sagittal plane hip, knee, and ankle angles were recorded at 66.7 Hz for 10 min during over-ground walking (Dingwell et al. 2000).

Multi-dimensional state spaces were reconstructed from each time series and its time-delayed copies (Takens 1981; Sauer et al. 1991). An embedding dimension of $d_E = 5$ was used (Dingwell and Cusumano 2000).

Locomotor complexity was defined from the correlation sum, $C(r, N)$, which quantifies how *geometric* correlations between points in state space scale with the distance (r) between those points (Kantz and Schreiber 1995; Dingwell and Cusumano 2000). “Self-

similarity” in chaotic systems produces linear variations of $\log[C(r, N)]$ with $\log[r]$. Because real-world systems often exhibit more complex structure, Local Scaling Exponents (LSE) were quantified from the local derivatives of $\log[C(r, N)]$ vs. $\log[r]$ (Fig. 1). As length scales (r) varied from very large to very small (Fig. 1: A \rightarrow D), the observable dimensionality of the system varied from a dimensionless point (LSE = 0) to a 1D limit cycle (LSE \approx 1) to more complex structures (Fig. 1C). At the smallest length scales, only high dimensional noise (LSE \approx $d_E = 5$) was observed (Kantz and Schreiber 1995).

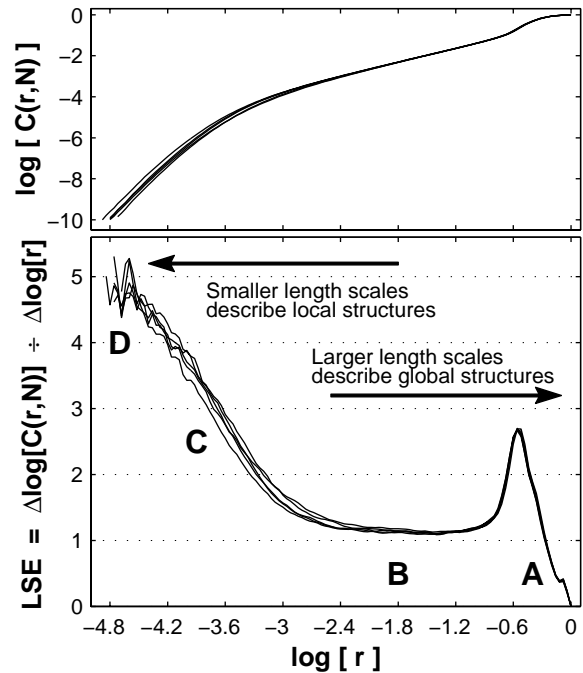


Fig. 1: Example of “Local Scaling Exponents” (LSE) defined as the local slopes of correlation integrals (top) computed from knee data of a typical subject.

It is believed that basic locomotor patterns are generated by spinal cord mechanisms. Sensory feedback acts mainly to modulate these patterns. Thus, it was hypothesized

that peripheral neuropathy would alter the apparent dimensionality of locomotor patterns on smaller length scales (Fig. 1C), but not at larger length scales (Fig. 1A & B).

LSEs curves were constructed for all subjects for all 6 time series. These curves were sub-sampled at evenly spaced intervals of $\Delta \log[r] = 0.6$ for statistical comparison. A repeated measures ANOVA tested for between-group differences using a Bonferroni correction for multiple comparisons.

RESULTS

NP patients exhibited greater LSEs than CO subjects at intermediate length scales *above* the noise floor, but *below* the range dominated by the global limit cycle dynamics (Fig. 2). Increased LSEs imply greater structural complexity of locomotor dynamics in NP patients. Similar increases occur when natural stride-to-stride fluctuations are replaced by correlated random noise (Dingwell and Cusumano 2000). This loss of deterministic structure implies a degradation of fine motor coordination in the control of NP gait.

A previously described multiple regression analysis procedure (Dingwell et al. 2000) demonstrated that differences in LSEs at the knee were significantly predicted by differences in sensory status, even after accounting for differences in strength, flexibility and walking speed. Differences in LSEs for the other kinematic variables were found to be related to a combination of intrinsic differences and differences in walking speed.

DISCUSSION

Peripheral sensory feedback does appear to play a role in reducing the complexity of locomotor kinematics. However, the present results indicate that even severe sensory loss produces only small increases in local dimensionality and only at those length scales where it was anticipated that sensory feedback would play the greatest role. The present results support the notion that sensory feedback plays a role in fine-tuning locomotor patterns, but not in generating the

global features of those patterns. Although it is still not clear how NP patients learn to compensate for their sensory loss, these results confirm the visual observation that peripheral sensory feedback is not “essential” for maintaining stable bipedal locomotion.

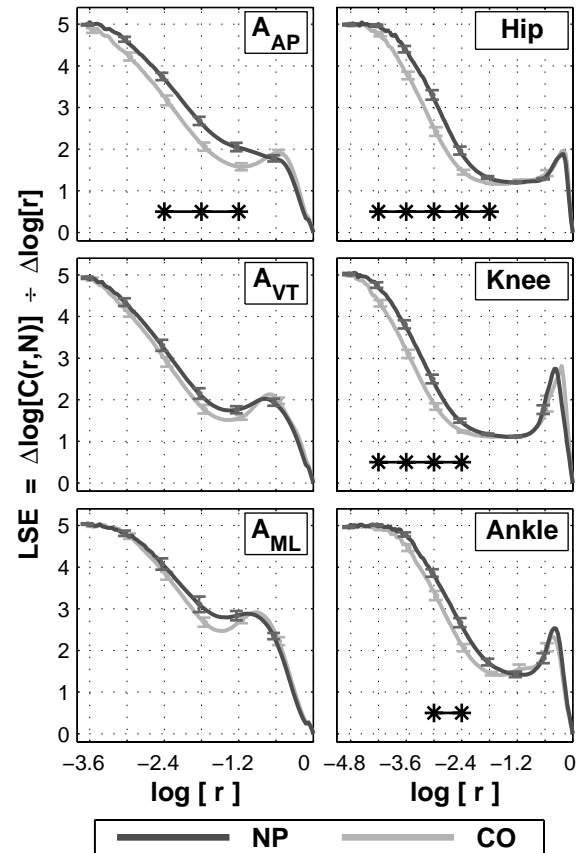


Fig. 2: Mean (\pm SE) local scaling exponents (LSE). Stars (*) indicate statistically significant differences between NP and CO groups.

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