EVIDENCE FOR GOAL EQUIVALENT CONTROL IN TREADMILL WALKING

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INTRODUCTION

Fluctuations in the repeated performance of human movements provide important information about the function and health of the neuromotor system (Osborne et al., 2005; Stein et al., 2005). In walking, reflexes are important for regulating gait cycle timing (Zehr & Stein, 1999). Thus, changes in appropriately defined measures of gait fluctuations should reflect changes in neuromotor control. This work uses the concepts of goal functions and goal equivalent manifolds (GEMs) (Cusumano & Cesari, 2006, Gates & Dingwell, 2008) to gain new insights into the nature and structure of neuromotor control humans use during treadmill walking.

GEM THEORY

The goal function for steady walking is

$$L_n - vT_n = 0\,, \tag{1}$$

Where v is treadmill speed, L_n is the length of stride n, and T_n stride time. The GEM is the set of all vectors (L_n, T_n) satisfying Eq. (1). We then decompose the perturbations $\boldsymbol{\delta}_n = (T_n, L_n) - (T^*, L^*)$ about the mean values (T^*, L^*) into components tangential and perpendicular to the GEM (Fig. 1) by

$$\boldsymbol{\delta}_n = \delta_T \hat{e}_T + \delta_P \hat{e}_P\,. \tag{2}$$

The speed of stride n is $v_n = L_n/T_n$. Linearizing about the mean values and transforming into perpendicular and tangential coordinates, one can show that

$$e_n = \left(\sqrt{1+v^2}/T^*\right)\delta_P\,, \tag{3}$$

where $e_n = v_n - v$ is the goal-level error, i.e., the deviation in stride speed from treadmill speed. Thus, perturbations along the GEM, δ_T, to lowest order have *no effect on walking speed*, whereas perturbations perpendicular to the GEM, δ_P, do. This means fluctuations in walking speed scale with those of δ_P as:

$$\sigma_e/\sigma_P = \sqrt{1+v^2}/T^*\,, \tag{4}$$

where σ_e and σ_P are the standard deviations in stride speed and deviation δ_P, respectively.

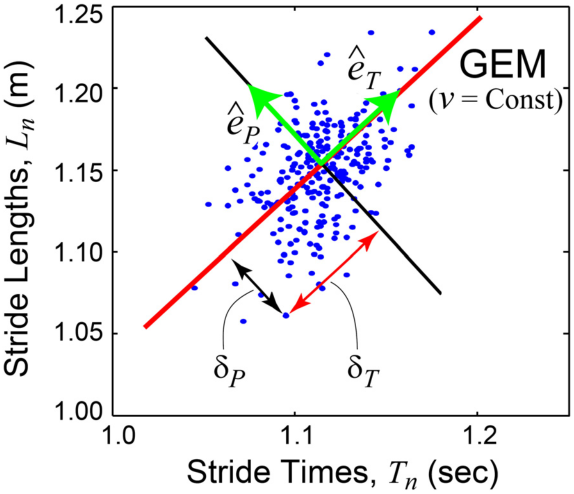

Figure 1 Stride times T_n and lengths L_n for each stride for a typical subject, showing the GEM and scalar deviations δ_P and δ_T.

We posit that the neuromotor control acts to drive the stride states onto the GEM, and are thus led to the following three hypotheses:

H1. The variability in δ_P will be significantly less than the variability in δ_T.

H2. The fluctuations in δ_P will show evidence of strong control, those in δ_T will show only weak control.

H3. The variability of walking speed will scale according to Eq. (4).

EXPERIMENTAL METHODS

17 healthy older (65-85 yr) subjects participated. Each subject walked on a level motorized treadmill (Woodway USA) at 5 speeds: preferred, ±10%, and ±20%. There were two

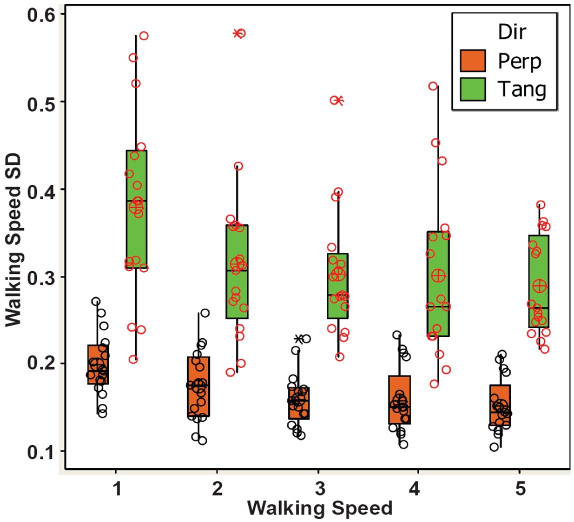

Figure 2 Walking speed variability perpendicular and tangent to the GEM.

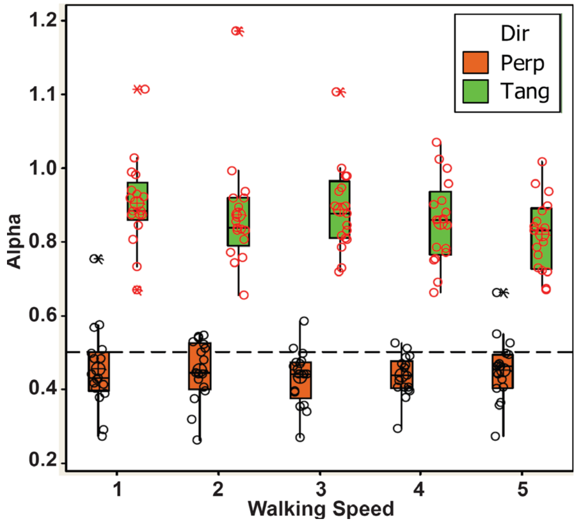

Figure 3 Detrended fluctuation results perpendicular and normal to the GEM

5 min trials at each speed. Stride lengths and times were computed from movements of 5 reflective markers attached to each foot (Vicon, Oxford Metrics, Oxford, UK). The GEM for each subject was constructed using their average speed across all strides. The time series of perturbations δ_P and δ_T were computed for each subject via Eq. (2), as in Fig. 1.

Detrended fluctuation analysis (DFA; Peng et al., 1992) was used to quantify the statistical structure of stride-to-stride variations in the perturbation time series. DFA yields a scaling exponent, α: $\alpha = 0.5$ indicates a white noise time series; $\alpha > 0.5$ implies *persistent* correlations (i.e., deviations in one direction are more likely to be followed by deviations in the same direction); $\alpha < 0.5$ implies *anti-persistent* correlations (i.e., positive and negative deviations are more likely to alternate).

RESULTS AND DISCUSSION

All subjects showed highly significantly ($p <$ 0.0005) smaller variability perpendicular to the GEM than tangent to it (Fig. 2). Also, across all subjects, the DFA analysis yielded α values highly significantly different ($p <$ 0.0005) in both directions: α tended to be under 0.5 for perturbations perpendicular to the GEM, indicating antipersistence consistent with error correcting control, whereas α was almost always over 0.5 for tangential perturbations, indicating long-range persistent correlations that are consistent with weak or indifferent control. Finally, the scaling behavior of Eq. (4) was satisfied by all subjects with an R^2 value in excess of 99%.

CONLUSIONS

All three hypotheses H1-H3 were satisfied, consistent with the theoretical task dynamical model developed using the concepts of goal-equivalence. The GEM was not found to be strictly "uncontrolled", however there is strong evidence that the GEM structure is used in maintaining a steady walking speed, at least for treadmill walking.

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