GOAL EQUIVALENT CONTROL OF VARIABILITY IN HUMAN WALKING

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INTRODUCTION

While increased gait variability has been linked to an increased risk of falls in the elderly, different gait variables exhibit different changes in variability with age and/or fall history (Brach et al. 2005; Moe-Nilssen & Helbostad, 2005). Thus, it is not clear which gait variables would be best to quantify.

For redundant tasks exhibiting equifinality, we can define an explicit mapping from variability in body movements to variability at the *goal* level of the task (Cusumano & Cesari, 2006). The *goal* of steady walking is to maintain constant speed, but many combinations of stride length (L) & stride time (T) achieve this goal. These (L, T) combinations define the "Goal Equivalent Manifold" (GEM) for walking (Fig. 1). Deviations of (L, T) *off* of the GEM negatively impact task performance (i.e., speed). Variations *along* the GEM do not. We tested the hypothesis that the temporal structure of the variability of movement deviations *along* the GEM defined for walking would differ from that for deviations *perpendicular to* the GEM.

METHODS

The goal function for steady walking is:

$$v = L_n / T_n \equiv Const \qquad (1)$$

where L_n is stride length at step n and T_n is stride time. For any constant speed v, the GEM is defined as the line $L_n = v \cdot T_n$ (Fig. 1). We then decompose the variability in L_n and T_n into variability tangent to $(\hat{e}_T)$ and perpendicular to the GEM $(\hat{e}_P)$ via:

$$\vec{\delta}_n = \left(\vec{\delta}_n \cdot \hat{e}_T\right)\hat{e}_T + \left(\vec{\delta}_n \cdot \hat{e}_P\right)\hat{e}_P \qquad (2)$$

where scalar deviations $\delta_T = \vec{\delta}_n \cdot \hat{e}_T$ are *goal equivalent*: they do *not* affect velocity, $\vec{\delta}_n$, but deviations $\delta_P = \vec{\delta}_n \cdot \hat{e}_P$ *do* directly impact speed (i.e., these are *goal-relevant* errors).

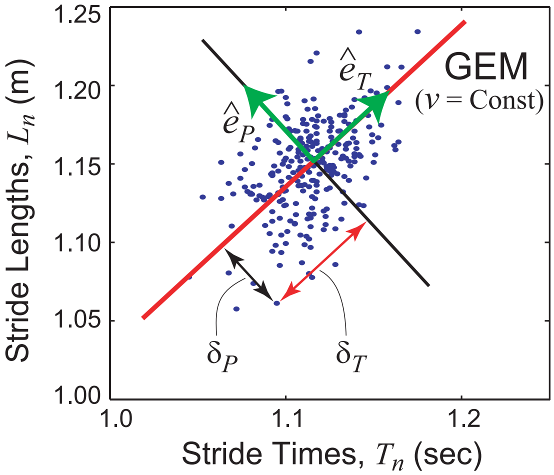

Figure 1: Stride times (T_n) and lengths (L_n) for each stride for a typical subject, showing the GEM and scalar deviations δ_T and δ_P.

Eighteen healthy elderly volunteers (age 65-85 yrs) walked on a level treadmill (Woodway USA) at their preferred self-selected constant walking speed. The 3D movements of reflective markers attached to their feet were recorded (Vicon, Oxford Metrics, Oxford, UK) continuously for 2 trials of 5 minutes and used to compute the stride length (L_n) and stride time (T_n) for each stride, n.

The GEM for each subject was constructed using their average speed across all strides, $\bar{v} = \langle L_n / T_n \rangle_n$. We then extracted time series of deviations tangent (δ_T) and perpendicular (δ_P) to each subject's GEM (Eq. 2; Fig. 1).

Detrended fluctuation analysis (DFA; Peng et al., 1992; Hausdorff et al., 1995) was used to quantify the statistical structure of stride-to-stride variations in these δ_T and δ_P time series. DFA yields a scaling exponent, α. $\alpha = 0.5$ indicates a completely random (i.e., uncorrelated) time series. $\alpha > 0.5$ implies "*persistent*" long-range correlations: i.e., deviations in one direction are more likely to be followed by more deviations in the same direction. $\alpha < 0.5$ implies "*anti-persistent*" correlations: i.e., positive and negative deviations are more likely to alternate.

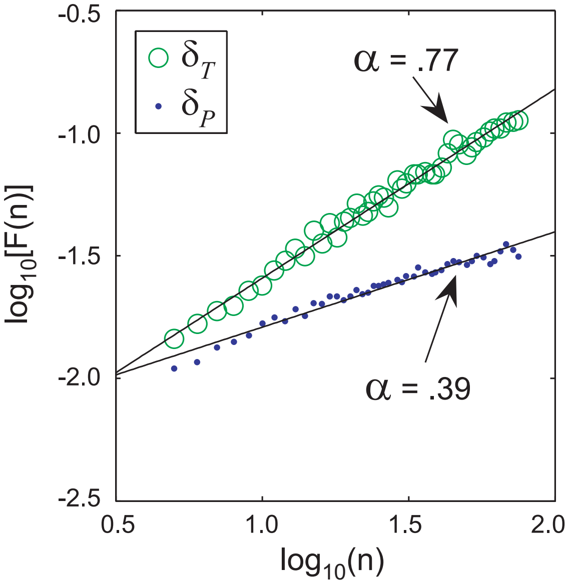

Figure 2: DFA results for deviations tangent to (δ_T) and perpendicular to (δ_P) the GEM for the data shown in Fig. 1. Similar results were obtained from all subjects.

RESULTS AND DISCUSSION

All subjects exhibited persistent long-range correlations for deviations *along* (δ_T) the GEM, but either no correlations or anti-persistence for deviations *perpendicular to* (δ_P) the GEM (Fig. 2). Across subjects, differences in correlation structure between δ_T deviations and δ_P deviations were highly statistically significant (Fig. 3).

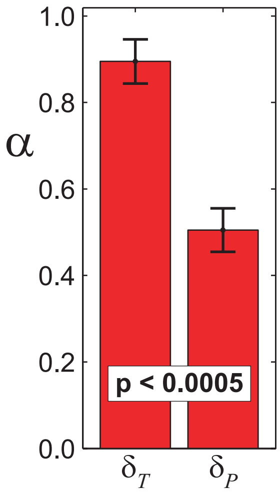

Figure 3: Means ± 95% confidence intervals for DFA slopes (α) for all 18 healthy elderly subjects for both δ_T and δ_P deviations off of the GEM. The difference between directions was highly significant ($p < 0.0005$).

SUMMARY/CONCLUSIONS

As hypothesized, the temporal structure of movement variations was significantly different *along* vs. *perpendicular to* the GEM. Deviations away from the GEM were far more likely to be redirected back towards the GEM than deviations along the GEM $[\alpha(\delta_P) << \alpha(\delta_T)]$. Thus, subjects applied greater active control to reduce these perpendicular deviations. The present approach may thus yield more appropriate variables for describing gait variability. Efforts are underway to determine how these results vary across age groups and walking speeds.

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