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:

\[ v = L_n / T_n \equiv \text{Const} \]

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:

\[ \delta_n = (\delta_n \cdot \hat{e}_T) \hat{e}_T + (\delta_n \cdot \hat{e}_P) \hat{e}_P \]  

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

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 ($\delta_T$) and perpendicular ($\delta_p$) 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 $\delta_T$ and $\delta_p$ time series. DFA yields a scaling exponent, $\alpha$. $\alpha = 0.5$ 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 ($\delta_T$) and perpendicular to ($\delta_p$) 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 ($\delta_T$) the GEM, but either no correlations or anti-persistence for deviations perpendicular to ($\delta_p$) the GEM (Fig. 2). Across subjects, differences in correlation structure between $\delta_T$ deviations and $\delta_p$ deviations were highly statistically significant (Fig. 3).

Figure 3: Means ± 95% confidence intervals for DFA slopes ($\alpha$) for all 18 healthy elderly subjects for both $\delta_T$ and $\delta_p$ 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.

REFERENCES