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LOCAL DYNAMIC STABILITY OF PASSIVE DYNAMIC WALKING ON AN IRREGULAR SURFACE

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INTRODUCTION

Previous experiments have shown that stride-to-stride fluctuations in human walking kinematics are statistically distinguishable from linearly filtered white noise [1]. However, the human musculoskeletal system is very nonlinear. Therefore, these nonlinear fluctuations may still be due to a white noise source (of either biological and/or environmental origin) that is being nonlinearly filtered by the mechanics of the system. If this were the case, the perturbations induced by this process should dissipate very quickly. The purpose of this study was to determine how quickly local perturbations from a purely white noise source dissipate in a mechanical model of walking.

METHODS

We modified an existing "simplest" model of passive dynamic walking [2] to allow us to examine the local dynamic stability characteristics [1,3] of walking in the presence of amplitude increasing white noise. Random perturbations were applied to the step transition constraint, making the task equivalent to walking down a "bumpy" slope (i.e., transitions occurred slightly earlier or later) The modified transition equation was:

$$\phi(t) - 2\theta(t) = \varepsilon \cdot U[-0.5, +0.5] \qquad (1)$$

where ϕ = the angle between the stance leg and the swing leg, θ = the angle of the stance leg with respect to the slope normal, and ε was the amplitude (in rad) of the uniform white noise, U, applied to the system. Five trials of 300 strides (600 steps) of perturbed walking were simulated for each of 6 perturbation amplitudes ($0 = \varepsilon = 0.1$ rad). All trials simulated walking down a slope of angle $\gamma = 0.009$ rad, corresponding to stable period-1 limit cycle motion. Per-turbations were applied randomly to each step in each trial.

We used a previously established method [1,3], to calculate exponential divergence for each trial for each perturbation amplitude. Mean log divergence was calculated out past 2.5 strides (5 steps) (Fig. 1A). Local dynamic stability, defined as the exponential *rate* of divergence, was quantified from the instantaneous slopes of these curves, using a standard 3-point difference formula.

RESULTS AND DISCUSSION

The amplitudes of the mean log divergence curves increased with increasing noise amplitude (Fig 1A). The slopes of the divergence curves, however, remained nearly identical (Fig 1B). Thus, the *rates* of divergence were controlled primarily by the inherent stability of the limit cycle motion, rather than by the amount of noise present. In fact, the rates of divergence dropped to near zero after only 2 steps, and were virtually zero after 3 steps.

This shows that this simple mechanical model of walking can dampen out the effects of these local perturbations very quickly. This capacity does not depend very strongly on the amplitude of the perturbations (i.e. noise amplitude).

In humans, local perturbations exhibit continued divergence for well beyond 10 strides [1]. The present results suggest that this extended divergence seen in humans may not be due exclusively to the nonlinear filtering properties of this highly nonlinear mechanical walking mechanism. Rather, these results provide additional evidence that suggests the source of the nonlinear fluctuations in experimental walking data is at least partly biological (e.g., possibly due to reflex mechanisms) in origin and is not purely mechanical.

Future work will refine the walking model by making it more anthropometric, adding knees, and adding more biologically inspired control mechanisms. These efforts will allow us to determine the relative influences of different types of both biological and environmental noise on the local dynamic stability of walking.

REFERENCES

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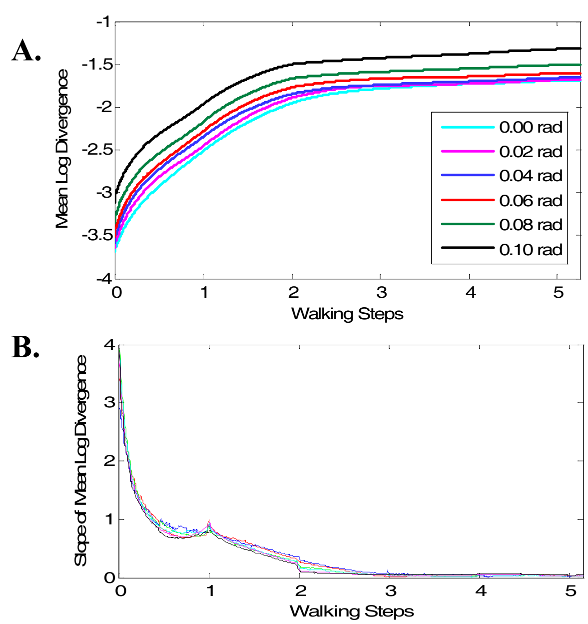

Figure 1: A. Mean log divergence curves averaged over 5 trials at each noise level. Divergence amplitudes increased for increasing ε (Eq. 1). **B.** Slopes of the divergence curves in **A**. Excluding the initial value, these curves were very similar. Note the slight jumps at steps 1 and 2. By the 3rd step, the divergence was negligible.