EFFECT OF SURFACE COMPLIANCE ON STEPPING RESPONSES TO TRUNK PERTURBATIONS

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INTRODUCTION

A disproportionate increase in falling injuries as people age has been well documented during walking (Woolley, 1997). Dynamic balance on a narrow beam has been found to be hindered by walking with thick, soft soles (Robbins *et al*., 1992). Compliant surfaces have been frequently used to challenge balance during upright stance, and thus would be expected to decrease the ability to maintain dynamic balance during walking.

To model walking, a trunk segment was added to a planar passive dynamic walker (McGeer, 1990). In addition to the legs modeled in the original model, the addition of trunk allows for the observation of trunk stability on overall system performance, and provided a rigid body with significant inertia to perturb.

This simulation explores the behavior of a passive dynamic walker after trunk perturbations in the sagittal plane, given different surface compliances that range from concrete to rubber mats.

METHODS

Model. The model consists of a four degree of freedom (4-DOF) passive walking system, which includes four point masses: one on each leg, one on the trunk, and one on the ground contact to model the mass of the ground segment underneath the body. The model was created in Matlab (Mathworks), using the equations of motion that were derived by Kane's Method in Mathematica (Wolfram Research), and utilizing non-dimensional parameters for the segment masses, moment of inertias, and lengths. The compact form of the equations of motion can be expressed as:

$$M(\phi)\ddot{\phi} = V(\phi,\dot{\phi}) + G(\phi) + T \qquad (1)$$

where the mass matrix, velocity vector, gravity vector, and torque vector are used, with respect to the segment angles. The stabilization of the trunk is achieved by assuming a 2-DOF system with damping and spring stiffness, whose parameters are determined from rough, experimental measurements. Perturbations are introduced by the use of a step input at the onset of a swing and are applied through the full duration of the step.

RESULTS AND DISCUSSION

Modeling Trunk Perturbations. The results of increasing positive torque or increase of negative force led to very similar segment characteristics behavior. Similarly, the increase in positive force was similar to the increase in negative torque (Figure 1). However, parameter studies revealed that an 8:10 relationship between torque and force ratios above at an initial torque magnitude of -0.3 consistently led to the highest energy losses during heelstrike.

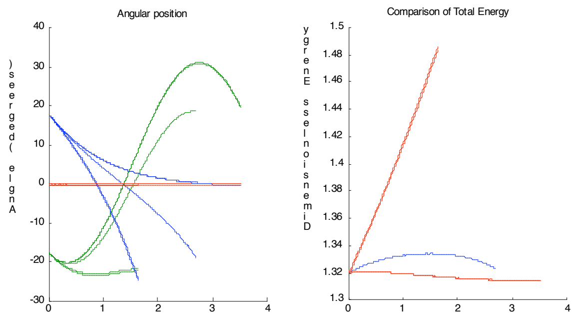

Figure 1: Segment kinematics and system energetics based on the limits of force/torque perturbations. All simulations considered a non-compliant surface.

Surface Compliance. The results from the comparison of surface compliance on system behavior during a step revealed the most significant effect in swing leg trajectory, in comparison with the stance leg (25% difference in swinging leg angle vs. 18% difference in stance leg angle). The total energy of the system demonstrated significant increases in energy fluctuation as the surface compliance increased, given the unperturbed condition (Figure 2).

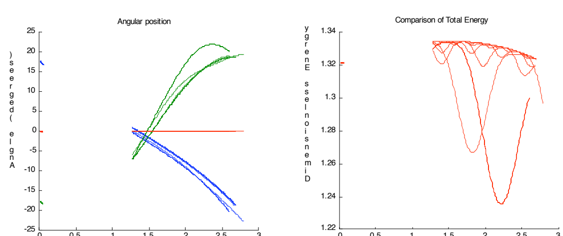

Figure 2: Effect of surface compliance on unperturbed system on segment kinematics and system energetics. Surface stiffness, K, values range from 4376 Nm to 14.4 Nm.

SUMMARY/CONCLUSIONS

The effect of either torque or force trunk perturbations were very similar on the boundary values of a normal gait, yet demonstrated subtle variations within a fixed range of perturbations. With respect to the local minima derived from the parameter study, the conditions that arise to produce an increase in the energy loss at heel strike makes intuitive sense, since those perturbation combinations both contribute to an increase in angular momentum during a forward step. The increased observed effect of angular momentum perturbations suggests that perturbations that lead to trunk bending could be more dangerous during walking. This effect can be physically explained by the increase in hip torques necessary to maintain trunk stabilization, which when acting on the stance leg would prompt a torque about the foot contact point and accelerate the stance leg forward toward the ground.

The addition of surface compliance led to significant changes in energy losses, yet revealed changes of less than 10% in the maximal angle deviations during an unperturbed gait. Similarities in segment trajectories under varied surface compliance conditions suggests that the body is capable of passively maintaining a desired center of mass trajectory, and therefore suggests that gait changes might be best explained by active control.

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