CONTROL OF BALANCE DURING WALKING IN YOUNG AND ELDERLY ADULTS

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INTRODUCTION

Balance ability decreases in older adults, due to age-related sensory, motor, and other changes. Human walking appears to be unstable in the lateral direction (Kuo, 1999; Bauby & Kuo, 2000), and relatively stable in the fore-aft direction. Age-related deficits in balance during walking may be most apparent in the lateral direction.

The stability of walking depends on the dynamics of the musculoskeletal system. The limb dynamics appear to be passively stable in the sagittal plane (McGeer, 1990). We developed a 3-d model incorporating roll motion (Kuo, 1999) and found that its fore-aft motion remained stable, but its lateral motion was unstable. This instability is controllable with feedback-driven lateral foot placement.

We previously presented a simple experiment measuring variability of foot placement during walking in young adults. We found that step variability was greater in the lateral direction and that walking with eyes closed had a greater effect on lateral variability (Bauby and Kuo, 2000), supporting the hypothesis that humans actively stabilize lateral, but not fore-aft, motions. Here, we repeat the experiment with elderly subjects. Our results again implicate active control in lateral balance and highlight the difficulty of this control for older patients.

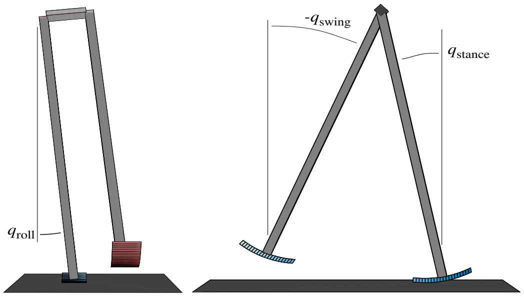

Figure 1: Three-dimensional passive dynamic walking model (Kuo, 1998). Left: Front view. Right: View from right.

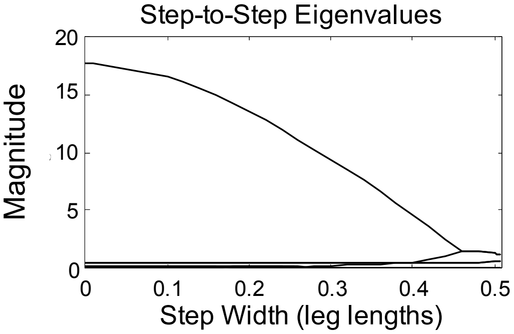

Figure 2: Eigenvalue magnitudes of the linear map as a function of step width. Instability decreases as step width increases, indicating a possible strategy for reducing lateral control requirements.

METHODS

3-D Passive Walking Model

Dynamics. The model consists of a pelvis and two legs (Fig. 1), with 3 degrees of freedom: a pin joint at the hip, rolling line contact with the ground, and a pin joint between the foot and leg allowing for lateral motion. Starting with the beginning of the swing phase, we forward integrated equations of motion until heel-strike, then modeled an inelastic collision using conservation of angular momentum. We employed 1^{st}-order shooting to find a fixed point, signifying a limit cycle. Local stability was evaluated in a discrete linear approximation of the nonlinear mapping. There is one unstable eigenvalue, mostly limited to the roll states. The magnitude of this eigenvalue decreases with increasing step width (Fig. 2).

Control. We studied several methods for stabilization, and found lateral foot placement particularly attractive since small adjustments prior to heel strike have large ef-

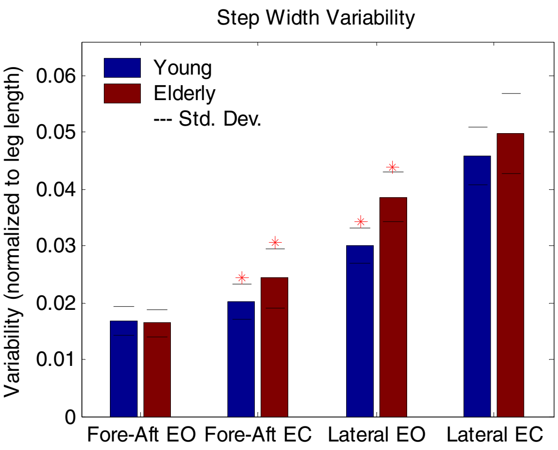

Figure 3: Foot placement variability under the eyes open (EO) and eyes closed (EC) conditions. * indicates significant difference ($p < 0.01$).

fects on the trajectory of the next step, while other methods have a larger energy cost (Kuo, 1998). We used pole placement to design a stabilizing feedback control law for once-per-step splay angle adjustments.

Human Walking Experiments

Our model indicates that limb dynamics and local reflex loops may be sufficient to provide passive fore-aft stability, but the CNS should find it necessary to stabilize lateral motions. Reducing sensory input to the controller of an unstable system leads to poorer overall control, with greater variability in the control signal. If the CNS actively stabilizes lateral balance through feedback-driven lateral foot placement, closing one's eyes should result in greater variability in lateral, but not fore-aft, foot placement. Reduced sensory precision associated with age should also cause an increase in lateral variability.

We measured foot placement in the natural overground gait of 15 young adult subjects, aged 18-40, and 13 elderly subjects, aged 64-82. Step parameters were measured using a mobile kinematic tracking system (Bauby & Kuo, 2000) as subjects walked at a self-selected speed in a straight line for at least 400 contiguous steps.

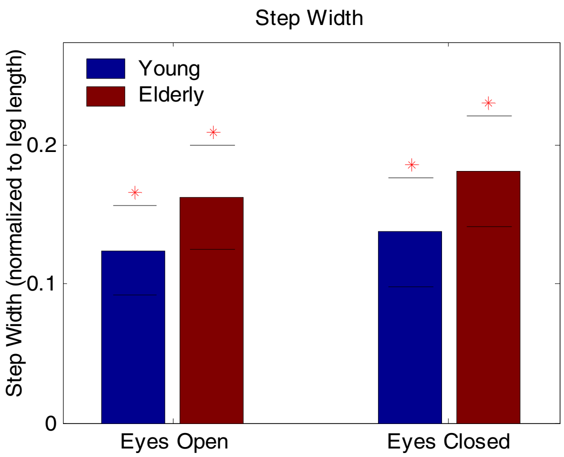

Figure 4: Mean step width. On average, elderly subjects' steps were 0.041 leg lengths (~1.52 inches) wider than those of young subjects.

RESULTS AND DISCUSSION

All subjects always had greater lateral than fore-aft variability ($p = 6.4e-8$). All subjects had increased lateral variability with eyes closed ($p = 1.7e-5$), with greater increases in lateral than fore-aft variability ($p = 0.009$, Fig. 3). Step width increased for all subjects with eyes closed ($p = 0.003$), and elderly subjects always took wider steps than young subjects ($p = 0.008$, Fig. 4), while maintaining similar step length.

These results are consistent with our hypothesis that the CNS utilizes sensory feedback to actively control lateral balance. Additionally, the increased step width of elderly subjects may indicate a strategy to reduce active control requirements, per Kuo (1999). The increases in fore-aft variability may be due to fluctuations in walking speed and the control coupling described by Bauby (2000).

ACKNOWLEDGEMENTS

Supported by NIH 1R29DC02312-01A1.

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