BALANCE RECOVERY BY STEPPING DURING BACKWARD FALLS

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INTRODUCTION

Stepping represents a primary means for balance recovery after a large unexpected perturbation, such as a slip or trip. However, little understanding exists of the biomechanical factors which govern this task. Previous studies have shown that elderly are less able than young to recover balance with a single step [Luchies, 1994; McIlroy, 1996; Thelen, 1997]. Yet, these studies have found little or no significant difference in step size or step contact time when age is considered. Therefore, from a biomechanical perspective, additional factors separating young, elderly, and the ability to recover balance with a single step, may be the capacity to develop sufficient "stiffness" in the stepping leg and the ability to position the leg such that it has an adequate mechanical advantage. In this study, the "stiffness" of the stepping leg after contact is reflected by the magnitudes and times to peak lower extremity joint torques. The mechanical advantage, or effective lever arm, of the stepping leg during step contact is defined by the ratio of the stepping angle at the instant of contact (α_C) and the body lean angle at contact (θ_C), which are related to the combined effect of step size and step contact time.

Accordingly, we tested the hypothesis that elderly subjects' ability to recover balance with a single step is better explained by the stiffness and mechanical advantage of the stepping leg during step contact, than by step size and step contact time. To test this hypothesis, we conducted simulated backward slipping experiments on elderly subjects aged 70 years and over.

METHODS

Twenty-six (12 female, 14 male) healthy, community-dwelling elderly adults, of mean age 75 ± 4 (S.D.) yrs, height 1.66 ± 0.11 m, and body mass 72 ± 15 kg, participated in the study. During the experiment, subjects were unexpectedly released by means of a tether and electromagnet from a backward inclination of seven degrees and instructed to recover balance with a single step (Fig.1(a)). During each trial, three-dimensional body segment positions and foot contact forces of the stepping leg were acquired via a 6-camera 60 Hz motion capture system and a force plate, respectively. Step contact time, stepping angle α_C (which reflects a normalized step size), and mechanical advantage α_C / θ_C were determined from the recorded motion data. Magnitudes and times to peak ankle plantarflexor, knee extensor, and hip flexor torques were estimated from the motion and force data by using inverse dynamics (Fig.1(b)). For each subject, average values based on five trials were included for analysis. Subjects were classified into three recovery ability categories: "single-steppers", who were successful at recovering balance with a single step in four or more trials, "multi-steppers", who were only successful in one or less trials, and "mixed" otherwise. Ensemble-average values were computed for each category based on subject averages.

RESULTS

Fifty percent of the subjects were single-steppers. The remaining subjects were split between being multi-steppers (27%) and mixed (23%). α_C / θ_C was the only factor which significantly associated with recovery ability ($p = 0.003$; via ANOVA). On average, single-steppers had the largest value of α_C / θ_C, 1.4 ± 0.5, while multi-steppers had the smallest, 0.6 ± 0.5 (Fig. 2). There were no significant differences with respect to recovery ability in step contact times (which averaged 360 ± 60 ms) or stepping angles ($13° \pm 7°$). Contrary to our hypothesis, no joint torque parameters were significantly different among the three categories. Average peak torques, normalized by body weight and height, at the hip, knee, and ankle were 0.066 ± 0.021, 0.062 ± 0.017, and 0.058 ± 0.17, respectively, while the average times to peak torque after contact were 100 ± 50 ms, 160 ± 90 ms, and 130 ± 40 ms, respectively.

DISCUSSION AND CONCLUSIONS

Although we had hypothesized that both the "mechanical advantage" and "stiffness" of the stepping leg during the contact phase would associate with the ability to recover balance with a single step, we found that only the mechanical advantage, as measured by the ratio α_c/θ_c, was significantly related to recovery ability in elderly individuals. As expected, step contact time and step size, alone, did not associate with recovery ability.

We found that subjects who predominately recovered their balance with a single step had a much larger value of α_c/θ_c than subjects who used multiple steps. Therefore, single-steppers placed their stepping leg in a position which provided a better mechanical advantage for halting the body's downward movement. Biomechanically, it would appear that one can compensate for a leg placement with a poor mechanical advantage by using a greater leg stiffness, or larger joint torques. Multi-steppers, however, used similar joint torques as single-steppers. These results may suggest that, while multi-steppers were performing at their maximum strength capacity, it was an inadequate leg placement that rendered their trials unsuccessful. Therefore, the ability to assess an individual's performance based on this new parameter α_c/θ_c may be very useful in determining her/his ability to succeed in restoring upright stance by stepping.

REFERENCES

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McIlroy, W.E. and Maki, B.E. (1996) *J Gerontol: Med Sci*, **51A**, M289-M296.
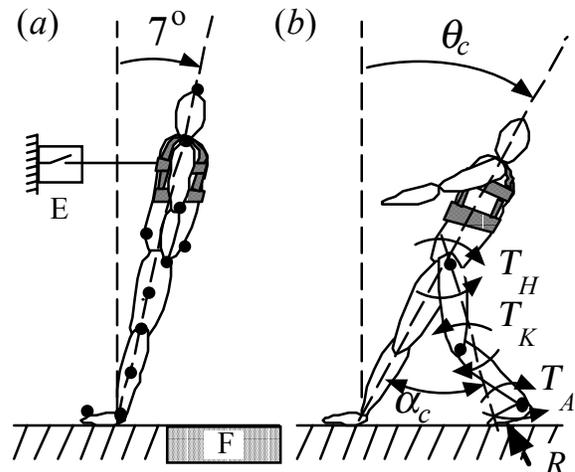Thelen, D.G. et al.(1997) *J Gerontol: Med Sci*, **52A**, M8-M13.

Figure 1. Backward slipping experiment. (a) The subject was held in a 7° inclination until the electromagnet (E) was released. Ground reaction forces on the stepping foot were recorded by the force plate (F). (b) The stepping angle (α_c) and body lean angle (θ_c) were determined at the instant of contact. Torques at the hip, knee, and ankle (T_H, T_K, T_A) were computed by inverse dynamics routines, starting from the reaction force R on the stepping foot upwards.
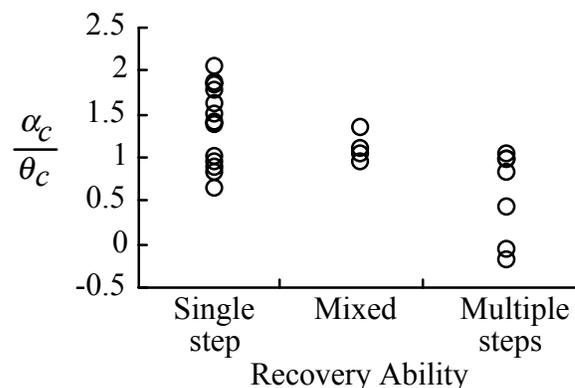

Figure 2. Subjects who recovered balance with a single step tended to position the stepping leg, during the contact phase of the step, such that it had a greater mechanical advantage (α_c/θ_c) than subjects who needed to take multiple steps.

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