EFFECTS OF STEP LENGTH ON BALANCE RECOVERY FROM A FORWARD FALL

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INTRODUCTION

Stepping responses are often used following balance perturbations to reconfigure the base of support [1]. Luchies et al. [2], using a backward waist pull perturbation, found that older adults (OA), compared to young adults (YA), stepped earlier, used a shorter initial step, and were more likely to employ a multiple step strategy instead of the single step strategy preferred by the young. The shorter step used by the OA may be coupled to their tendency to initiate a step earlier in their response, and thus may represent a motor program initiated as fast as possible. Thus, the current study explored the relationship between step length and step timing in YA. We tested the hypothesis that if YA take an initial step shorter in length, they too would initiate their step earlier in their response. If step initiation and step length are decoupled, then the YA would modify step length without modulating step timing. This would suggest that factors other than step length (e.g. greater fear of falling) might underlie the tendency of OA to step earlier following a perturbation.

METHODS

Participants

Twelve healthy young male adults (mean age 22, SD 3.3 years) participated in this study after providing written informed consent as approved by the institution's human subjects review board. All participants were recruited from university students and staff; denied significant head trauma, musculoskeletal impairments, and neurological disease; and were paid for their participation.

Tasks

A sudden release from a static forward lean introduced a fall-provoking disturbance [3,4]. Step length was manipulated by instructing the participant to use a natural length step, a smaller, and a larger than natural length step to regain his balance after the lean and release. Five trials were performed for each task in a random order, resulting in 15 trials for each participant.

Experimental Measures

Force and motion data were collected for 3 seconds with sampling rates of 1000 and 100 Hz, respectively. Three AMTI (Watertown, MA, USA) force plates were used to measure the foot-support surface reactions at the initial location of the left and the right feet and the landing location of the right foot. A Futek (Irvine, CA, USA) load cell measured the safety harness load and a custom-built load cell measured the lean-control cable tension. Force data were recorded on a personal computer running LabVIEW (National Instruments, Austin, TX, USA) through a 16-bit A/D data acquisition card (National Instruments). An Optotrak (Northern Digital, Inc., Waterloo, Ontario, Canada) motion analysis system was used to measure step foot kinematics throughout each response and to manually digitize initial feet positions for base of support calculations.

Data Analysis

The step response was quantified using temporal (pushoff time, liftoff time, landing time, and balance recovery time) and kinetic (force impulses at landing and center of mass trajectories in relation to the base of support) variables. Data from all trials were processed using MATLAB (Mathworks, Natick, MA, USA). Force and motion data were digitally low-pass filtered using a second order Butterworth filter with cutoff frequencies of 30 and 6 Hz, respectively.

Disturbance onset was defined as the time at which the cable tension dropped to zero. Pushoff time was defined as the time at which the force exerted by the stepping foot initially decreased to a local minimum force prior to increasing in preparation for weight transfer. Liftoff and landing times were defined as the time at which the vertical force exerted by the stepping foot initially dropped below the threshold of 15 N, and then rose above 15 N, respectively. Weight transfer time was defined as the difference between pushoff and liftoff times, and swing phase duration was defined as the difference between liftoff and landing times. The temporal events were used to divide the response into three regions: double stance, single stance, and landing regions of the response.

Center of pressure (COP) location was calculated using the foot-support surface reactions. Balance recovery time was defined to occur when the COP reached a maximum anterior position within a 500 ms window following the time when the forward momentum had been arrested.

Center of mass (COM) was calculated by double integrating the acceleration as described by Lyon and Day [5]. The anterior distance was calculated between the COM position at balance recovery and the edge of the base of support (BOS), which was defined as the anterior-most position of the digitized foot outline. The force impulse was determined in all three directions by numerically integrating the force record with respect to time between landing and balance recovery times.

Statistical Analysis

All data was statistically analyzed using SPSS 9.0 (SPSS Inc., Chicago,IL, USA). Means for each outcome variable were calculated across the five trials for each task, and a one-way analysis of variance (ANOVA) was used to determine any significant between-task differences for the outcome variables. Follow-up pairwise comparisons were performed in order to test for differences between pairs of tasks. A $p=0.05$ was considered to be statistically significant for all analyses.

RESULTS

Task had no effect on pushoff time or liftoff time, but there was a significant task effect on swing time, landing time, and balance recovery time. The large step task, compared to small, had significantly longer landing time ($p<0.01$) and swing phase duration ($p<0.005$). Recovery time was shorter for the small step task compared to the natural ($p<0.05$) and large ($p<0.005$) step tasks (Figure 1).

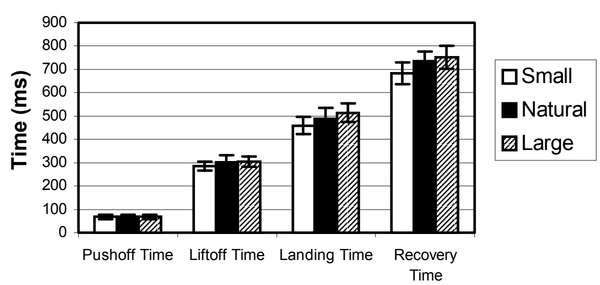

Figure 1. Temporal variables

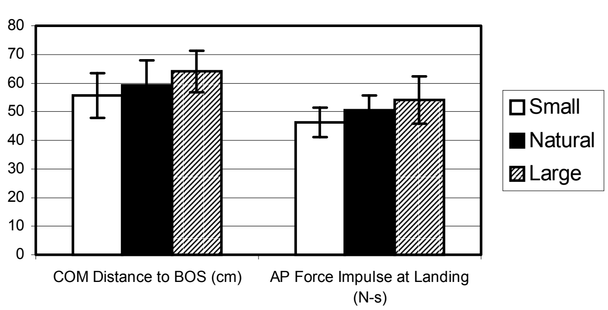

Figure 2. Kinetic variables

Task had a significant effect on the AP distance between the COM and the anterior limit of the BOS at recovery time. This distance was significantly smaller for the small step task compared to the large step task ($p<0.05$). Significant task effects were also observed for the AP force impulse at landing. This impulse was significantly smaller during the small step task compared to the natural ($p<0.05$) and large ($p<0.001$) step tasks (Figure 2).

DISCUSSION

Our results support the idea of an invariant preparation phase when recovering balance as proposed by Do et al. [3]. In that study, lean angle was modified and it was found that participants adjusted step length rather than step liftoff time to recover balance. In the current study, in which we held lean angle constant and asked the participants to voluntarily modulate step length, we found a similar invariant preparation phase in that the participants did not adjust step pushoff or liftoff times. Thus the data does not support our hypothesis that YA, when taking shorter steps similar to OA, would initiate their response earlier in a manner similar to that observed in OA [2]. This demonstrates a decoupling between step length and step liftoff time in the YA, and suggests that factors other than step length (e.g. greater fear of falling) might underlie the tendency of OA to step earlier following a perturbation.

Shortening the step length reduced the biomechanical demands of the task. The small step task, compared to larger step tasks, was characterized by both a smaller AP force impulse during landing and an earlier balance recovery time. Since AP momentum is directly related to the biomechanical strength requirements necessary to produce a balance-restoring moment, it may be concluded that less stringent strength requirements exist for smaller steps. However, the final COM position was significantly closer to the anterior edge of the BOS when using a short step response compared to a long step response, suggesting that the shorter step response came at the cost of a reduced margin of safety. Since the young adults in the current study were capable of using a short step length but did not choose to do so naturally, the young apparently do not optimize recovery time or minimize peak biomechanical loads when choosing and implementing a motor control program to recover balance.

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