



Age-related differences in the maintenance of frontal plane dynamic stability while stepping to targets



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ABSTRACT

Older adults may be vulnerable to frontal plane dynamic instability, which is of clinical significance. The purpose of the current investigation was to examine the age-related differences in frontal plane dynamic stability by quantifying the margin of stability and hip abductor moment generation of subjects performing a single crossover step and sidestep to targets that created three different step widths during forward locomotion. Nineteen young adults (9 males, age: 22.9 ± 3.1 years, height: 174.3 ± 10.2 cm, mass: 71.7 ± 13.0 kg) and 18 older adults (9 males, age: 72.8 ± 5.2 years, height: 174.9 ± 8.6 cm, mass: 78.0 ± 16.3 kg) participated. For each walking trial, subjects performed a single laterally-directed step to a target on a force plate. Subjects were instructed to “perform the lateral step and keep walking forward”. The peak hip abductor moment of the stepping limb was 42% larger by older adults compared to younger adults ($p < 0.001$). Older adults were also more stable than younger adults at all step targets ($p < 0.001$). Older adults executed the lateral step with slower forward-directed and lateral-directed velocity despite similar step widths. Age-related differences in hip abduction moments may reflect greater muscular effort by older adults to reduce the likelihood of becoming unstable. The results of this investigation, in which subjects performed progressively larger laterally-directed steps, provide evidence that older adults may not be more laterally unstable than younger adults. However, age-related differences in this study could also reflect a compensatory strategy by older adults to ensure stability while performing this task.

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1. Introduction

Previous investigations have suggested older adults may be vulnerable to frontal plane dynamic instability (Hall and Jensen, 2002; Hilliard et al., 2008; Maki et al., 2000; McIlroy and Maki, 1996; Mille et al., 2005), which is of clinical significance. A degraded ability to maintain control of frontal plane center of mass (COM) motion with respect to the base of support (BOS) could increase fall risk. The extent to which disturbances to lateral balance while walking relate to the ability of healthy older adults to maintain frontal plane dynamic stability is not known.

Frontal plane dynamic stability is highly regulated on a step-by-step basis while walking (Hof et al., 2007; Hurt et al., 2010; Rosenblatt and Grabiner, 2010). Swing foot placement establishes a distance between the COM and the base of support, creating the initial conditions to control frontal plane COM motion (i.e., COM position and velocity) and ultimately frontal plane dynamic

stability. After heelstrike, hip abductor moment generation during the stance phase decelerates the laterally-directed COM motion and redirects the COM medially (MacKinnon and Winter, 1993; Pandy et al., 2010). For normal walking conditions, compensation for deficiencies in control of COM kinematics may occur on a step-to-step basis to allow for safe community ambulation (Schrager et al., 2008). Thus, assessing the robustness of the central nervous system to control COM motion requires that tasks must create a greater challenge to dynamic stability compared to undisturbed walking.

Laterally-directed steps are commonly utilized while walking in the community to circumvent obstacles or to avoid undesirable step locations. These laterally-directed steps require an increased displacement and velocity of the COM that must then be arrested and reversed if the previous direction of travel (i.e., forward) is to be regained. Manipulating the spatial aspects of the step (i.e., lateral step distance) scales the difficulty of the task due to the larger lateral velocity. This may be more difficult for older adults given the significant reduction in peak isometric and isokinetic abductor moment production compared to younger adults (Johnson et al., 2004). Laterally-directed steps represent a functional task that requires both muscular strength and power to ensure frontal plane dynamic stability is maintained.

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Two lateral-step strategies have been identified as compensatory stepping responses to external postural disturbances (Hurt et al., 2011; Maki et al., 2000), but can also be performed while walking. One is a sidestep (SS) in which the stepping limb moves ipsilateral to the step direction. The second is a crossover step (COS), in which the stepping limb crosses in front of the stance limb and extends laterally away from the midline of the body. These step strategies can also be utilized to perform a lateral step while walking, and thus represent a task with ecological validity. The purpose of the current investigation was to examine the age-related differences in frontal plane dynamic stability by examining the margin of stability (Hof et al., 2005) and hip abductor moment generation of subjects performing a single COS and SS to targets that created three different step widths during forward locomotion. This provided a graded challenge to frontal plane stability. Due to the aforementioned decrease in peak ab/adductor strength and power of older adults compared to younger adults (Johnson et al., 2004), we hypothesized we would observe a significantly smaller peak abduction moment by older adults compared to younger adults during the stance phase of the lateral step, particularly at the longer step targets. Similarly, we hypothesized older adults would be less dynamically stable at heelstrike, while performing COS and SS than younger adults, particularly at the longer step targets for which the largest abduction moments would be expected.

2. Materials and methods

Nineteen young adults (9 males, 10 females, age: 22.9 ± 3.1 years, height: 174.3 ± 10.2 cm, mass: 71.7 ± 13.0 kg) and 18 older adults (9 males, 9 females age: 72.8 ± 5.2 years, height: 174.9 ± 8.6 cm, mass: 78.0 ± 16.3 kg) volunteered to participate in this study. Subjects were excluded from participation if they affirmed any neurological, musculoskeletal, or other injuries or disorders that would limit their functional mobility. Older adults were also excluded if they required an assistive device to walk or if the bone mineral density of their left proximal femur was less than 0.65 g/cm^2 (Cummings et al., 1993), as measured using dual energy X-ray absorptiometry (Hologic QDR 1000, Waltham, Mass., USA). All subjects provided written informed consent prior to participation in this institutionally reviewed and approved study. Self-ratings of general health were assessed by the physical functioning subsection of the Medical Outcome Survey 36-item short form health survey (Ware and Sherbourne, 1992).

Subjects walked along an eight meter carpeted walkway (Fig. 1) and performed a single COS or a SS, with their dominant limb to targets placed at three locations on a force plate imbedded in the walkway surface (Fig. 1). Limb dominance was assessed with the Revised Waterloo Footedness Questionnaire (Elias et al., 1998). Subjects initially performed five normal walking trials. They then performed five trial each of SS and COS trials at each of the short, long and medium distances, which were performed in the same order for all subjects. A demonstration of the steps was provided by the investigator. Subjects were instructed to “perform the lateral step

and keep walking forward”. The instructions ensured that individuals would keep walking forward after performing the lateral step requiring them to arrest the lateral motion thus providing a greater challenge to frontal plane dynamic stability.

The motions of 22 passive reflective markers were recorded by an eight-camera motion capture system recording at 120 Hz (Motion Analysis, Santa Rosa, CA) and filtered using a 6 Hz zero-lag low-pass Butterworth filter. The three-dimensional marker positions were tracked using commercial software (Cortex, Motion Analysis, Santa Rosa, CA), and analyzed off-line using custom Matlab software (MathWorks, Natick, MA). Kinematic variables were quantified from a twelve-segment model generated from the three-dimensional marker positions. The position of each subject's COM was calculated using anthropometric estimations (Winter, 2005). Step width was calculated as the distance in the frontal plane between the estimated foot centroids sampled at successive midstances. Step length was calculated as the fore-aft distance between foot centroids when the foot was flat on the floor. The velocity of the COM (vCOM) was calculated using a first-central difference algorithm, and used to quantify average forward step vCOM and peak lateral vCOM on a step-by-step basis. The medio-lateral vCOM was always positive towards the lead stepping limb. For the lateral step trials, these values were extracted from a window, defined from a given heelstrike to the contralateral heelstrike.

Ground reaction forces were collected from the force plate where stepping targets were placed (AMTI, Newton, MA, Fig. 1), and sampled at 1200 Hz. Inverse dynamics were computed from the synchronized motion capture and force plate data using a commercial software package (Orthotrak, Motion Analysis Corporation, Santa Rosa, CA). The internal frontal plane hip joint moment, which is bimodal in form, and primarily an abduction moment, was of particular interest. The initial abduction peak relates to arresting and redirecting the lateral velocity of the COM (Pandy et al., 2010), and thus, this value was used to characterize the peak hip joint abduction moment normalized by body mass. We also quantified continuous frontal plane muscular power of the hip with respect to the hip ab/adductor moment and the angular velocity of the limb ab/adduction angular motion. We were particularly interested in the peak negative hip power, which relates to energy absorption and occurred during the first half of stance phase.

For this investigation, we quantified dynamic stability as the relationship between the frontal plane position and velocity of the COM, with respect to the lateral edge of the base of support (Hof et al., 2005). The position and velocity of the COM within the frontal plane were used to define the extrapolated COM (xCOM: Eq. 1). The velocity of the COM was normalized by the eigenfrequency, or natural frequency, of a non-inverted pendulum with length 1.34 times the trochanteric height (ω_0) (Massen and Kodde, 1979)

$$\text{xCOM} = \text{COM} + \text{vCOM} / \omega_0 \quad (1)$$

Dynamic stability is quantified using the margin of stability (MOS), which can quantify stability on a step-by-step basis. The MOS considers the distance between the xCOM and the lateral border of the BOS (Hof et al., 2005) (Eq. 2). Negative MOS value is indicative of the need for a compensatory reaction to resolve the unstable condition

$$\text{MOS} = \text{BOS}_{\text{lat}} - \text{xCOM}. \quad (2)$$

The lateral border of the BOS was calculated with respect to the positions of the heel and toe markers that were used to compute the angle of toe-in or toe-out for a given step, and anthropometric estimations of foot width (Rosenblatt and Grabiner, 2010). The MOS was quantified at heelstrike (MOS_{hs}).

For this experiment, we tested the hypothesis that following foot placement the stepping limb peak hip abduction moment of the older adults would be significantly smaller than younger adults, particularly at the longer step targets. The hypothesis was tested using a three-factor ANOVA, Step (COS vs. SS) $\times$ Target (long, medium, short) $\times$ Age (older vs. younger), with repeated measures on the Step and Target terms and a between factors term on Age. We tested the hypothesis that older adults would be less dynamically stable at heelstrike than younger adults, particularly at the longer step targets by utilizing a three-factor ANOVA (Step $\times$ Target $\times$ Age) with repeated measures on the Target and Step terms and a between factors term on Age. To test whether step widths of individuals stepping to targets was different between groups, a three factor ANOVA was performed.

As secondary analyses we also tested differences in the forward directed vCOM and peak lateral vCOM with two mixed three-factor ANOVA with repeated measures on the Target and Step terms. For instances in which significant interactions of interest were detected, follow-up tests were performed on the simple comparisons with Bonferroni corrections applied for the number of comparisons made. We also quantified the step angle (i.e., $\text{atan}(\text{step width/step length})$), to descriptively compare the deviation of individuals from the direction of walking when performing the laterally-directed step. Finally, in the event of a significant difference in peak hip abduction moment, we compared peak negative hip power using preplanned pairwise comparisons of the effect of age on COS at the three different step distances and SS at the three different step distances using independent *t*-tests with a Bonferroni correction for number of comparisons made. Inclusion of this analysis was carried out to determine whether differences in peak hip moment generation resulted in age-related difference in peak hip absorption power. Significance was set at $p < 0.05$ unless corrections were applied. Effect size was reported as Cohen's *d*. All statistics were performed with SPSS 17.0 (IBM Armonk, NY).

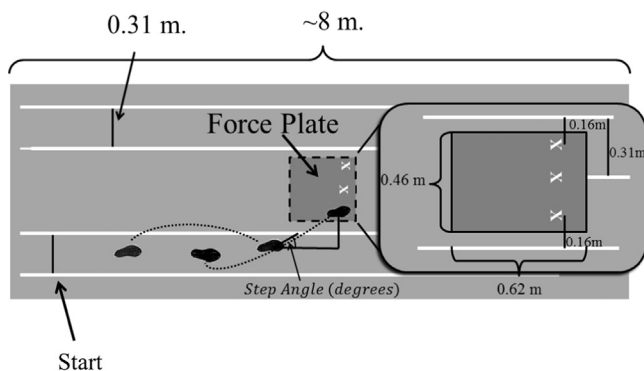


Fig. 1. Schematic diagram of the experimental setup used for this protocol. All lateral steps were performed with the individual's dominant limb as the lead limb. For instance, for a right limb dominant individual performing a crossover step (see foot pattern above), the individual would start the trial in the lane to the right of the force plates and would take the step towards the subjects left. Conversely, the same individual would perform a sidestep by beginning the walking trial in the lane to the left of the force plates and execute the step to the subject's right. Also illustrated are the targets to which subjects stepped during the data collection (inset).

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