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Lateral step initiation behavior in older adults

Patrick J Sparto,

Departments of Physical Therapy, Otolaryngology and Bioengineering, University of Pittsburgh

J Richard Jennings,

Department of Psychiatry, University of Pittsburgh

Joseph M Furman, and

Departments of Otolaryngology, Physical Therapy, and Bioengineering, University of Pittsburgh

Mark S Redfern

Departments of Bioengineering, Otolaryngology, and Physical Therapy, University of Pittsburgh

Abstract

Older adults have varied postural responses during induced and voluntary lateral stepping. The purpose of the research was to quantify the occurrence of different stepping strategies during lateral step initiation in older adults and to relate the stepping responses to retrospective history of falls. Seventy community-ambulating older adults (mean age 76 y, range 70–94 y) performed voluntary lateral steps as quickly as possible to the right or left in response to a visual cue, in a blocked design. Vertical ground reaction forces were measured using a forceplate, and the number and latency of postural adjustments were quantified. Subjects were assigned to groups based on their stepping strategy. The frequency of trials with one or two postural adjustments was compared with data from 20 younger adults (mean age 38 y, range 21–58 y). Logistic regression was used to relate presence of a fall in the previous year with the number and latency of postural adjustments. In comparison with younger adults, who almost always demonstrated one postural adjustment when stepping laterally, older adults constituted a continuous distribution in the percentage of step trials made with one postural adjustment (from 0% to 100% of trials). Latencies of the initial postural adjustment and foot liftoff varied depending on the number of postural adjustments made. A history of falls was associated a larger percentage of two postural adjustments, and a longer latency of foot liftoff. In conclusion, the number and latency of postural adjustments made during voluntary lateral stepping provides additional evidence that lateral control of posture may be a critical indicator of aging.

Keywords

biomechanics; balance; posture; aging; falls

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Corresponding Author: Patrick Sparto, Department of Physical Therapy, 6035 Forbes Tower, University of Pittsburgh, Pittsburgh, PA 15260, psparto@pitt.edu, 412-647-8069 (V), 412-647-0108 (F).

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Conflict of interest statement

The authors do not have any financial or personal conflicts of interest related to this research.

Introduction

Much research has been devoted to examine the intrinsic and extrinsic factors leading to falls. For example, Robinovitch et al. (2013) analyzed video-recordings of falls from common living areas of long-term care facilities.¹ They documented that incorrect weight shifting (e.g. leaning too far during standing or walking, improper foot placement during walking) was the most frequent cause of falling, encompassing 41% of the falls.¹ These findings underscore the need to investigate postural responses that occur during balance and gait activities in older adults.

Whereas young adults generally display consistent postural reactions across subjects, the behavior of older adults is more variable. In response to lateral surface perturbations that required a step to regain equilibrium, older adults were more likely to generate multiple steps, use arm reactions, and have collisions between legs than younger adults.² Similar findings occurred when lateral perturbations were induced by a waist-pull.³ While perturbed lateral stance has been shown to induce greater lateral body movement in persons with a history of falls,⁴ it is unclear if similar deficits in lateral balance control among fallers occurs during voluntary stepping. During voluntary lateral step initiation, older adults demonstrated different postural responses compared with younger adults.⁵ Whereas younger adults were able to step by directly unloading their stepping limb, on average, older adults had greater loading of their stepping limb, suggesting that they adopted a more conservative strategy of shifting their center of mass toward their stance limb.⁵ In a recent study, we have observed evidence of two different strategies of lateral step behaviors in older adults: 1) a direct unloading of the stepping limb, consistent with the strategy adopted by younger adults, and 2) a small initial loading of the stepping limb, consistent with the more conservative strategy.⁶ The frequency of occurrence of these strategies in older adults has not been determined.

The purpose of this study was to more formally describe and investigate weight shifting behaviors during voluntary lateral stepping in older adults. A secondary aim was to relate lateral stepping behavior to retrospective recollection of falls. The reason for concentrating on lateral step behaviors is that the control of postural reactions in the lateral direction appears to be related more to a history of falling than control in the anterior-posterior direction.⁷ In addition, because the use of a strategy that includes more postural adjustments necessarily increases the time for taking a step, and longer step times may prevent someone from making a timely protective step, we hypothesized that the step behavior may be related to fall history. The data described in this study augment the data reported in the prior study,⁶ by increasing the number of subjects in the sample (from 40 to 70), and by examining the relationship between stepping behavior and history of falls in the past year.

Methods

Subjects

Seventy (29 male, 41 female) community-ambulating healthy older adults participated in the study (mean age 76, SD 5, range 70–94 y). Twenty younger adults (10 male, 10 female, mean age 38, SD 11, range 21 – 58 y), who had performed the test during another experiment (unpublished data), were also included as a comparison group. After providing informed consent, subjects were screened to exclude a history of neurological, cardiopulmonary, or orthopaedic disease that would limit their mobility and balance function. Additional exclusion criteria included: taking psychoactive medications (e.g. benzodiazepines), poor peripheral sensation function, and poor neurocognitive function.⁸ Retrospective history of falling was measured using a falls history screening questionnaire

in which subjects were asked if they had a fall in the past year. The study was approved by the local Institutional Review Board.

Procedures

Two blocks of a simple reaction time task was performed, in which subjects stepped in response to an arrow displayed on a 46 cm diagonal cathode ray tube monitor, at a distance of 1 meter from the subject. The arrows (4° horizontal and 2° vertical visual arc) were generated by E-Prime 1.1 (Psychology Software Tools, Pittsburgh, PA). In the first block, a left pointing arrow appeared on the left side of the monitor, and in the second block, a right pointing arrow appeared on the right side of the monitor. Two catch trials in which no arrow was displayed appeared in random order among the other stimuli. Prior to each block, subjects were told which direction the arrow would be pointing, and practiced a few steps in that direction to generate consistent step lengths, about 25% of the subject's leg length. The block duration was 3 minutes with trials occurring every 7–9 s; each block contained 22 arrow stimuli and 2 catch trials.

Subjects wore a harness attached to an overhead carriage in order to prevent a fall from occurring. They stood on two independent force plates (Bertec Corp. BP5050, 50×50 cm) that recorded vertical ground reaction forces (VGRF) under each foot. The stance width for all subjects was 24 cm. Subjects wore their own low-heeled shoes and stepped to the left or right with the appropriate leading leg and followed with the trailing leg so that both feet came to rest lateral to the starting position. Subjects were instructed to step as quickly as possible when the visual cue appeared, without worrying about the exact landing location of their foot. The visual cue appeared only when the subjects were equally supporting weight on both legs. Subjects were given verbal feedback to equalize their weight distribution if needed.

Ground reaction forces and moments were recorded from the force plate at a sampling frequency of 1000 Hz. The time series of the VGRF of the stepping leg was used in the primary analysis (Figure 1). Stepping behavior was ascertained by counting the number of postural adjustments (PA) in the VGRF curve, defined simply as a change in polarity of the slope. This is not to be confused with the term “anticipatory postural adjustment (APA)” that appears in the literature. The PA represents a change in state of loading (positive slope) and unloading (negative slope) of the stepping limb. In practice, the PAs were determined as the time at which the derivative of the VGRF exceeded or fell below a threshold of 2% body weight per second. The latency and magnitude of the PAs at these times were computed using a customized interactive graphical user interface programmed in Matlab (Mathworks, Inc). The time of the first deflection of the VGRF from 50% body weight was defined as the latency of the first postural adjustment (PA₁), and the point when the VGRF fell to 0% body weight as the liftoff time (LO).

Statistical Analysis

A frequency count of the number of trials that had one, two, three or four postural adjustments was performed for each subject. In order to examine if there was a relationship between a subject's stepping behavior (i.e. frequency of trials with one or two postural adjustments prior to foot liftoff) and the latency of PA₁ and LO, older subjects were assigned to 3 groups based on splitting the percentage of single postural adjustment trials into tertiles. ANOVA was used to test if the median latency of the PA₁ and LO differed between groups, based on all stepping trials. The latency of the PA₁ was of interest because it represents the subject's reaction time. The latency of the LO was analyzed because it represents the functional outcome of the sequence of postural adjustments, in that it is the time at which the subject has irrevocably committed to taking a step in a certain direction.

The direction of stepping did not significantly affect the latencies, so the left and right stepping trials were combined. Post-hoc pairwise differences were assessed using a Tukey adjustment. The relationship between stepping behavior and fall history was explored using logistic regression. The dependent measure was the presence of a fall in the previous year, and the predictor variables were the percentage of trials with one and two postural adjustments, the median latency of PA₁ for all steps, and the median latency for LO for all steps. The data from younger subjects was used for reference, and not included in any statistical analysis.

Results

Stepping behavior

The VGRF time series of the stepping leg displayed two primary profiles. (Figure 1) In one profile, the VGRF decreased monotonically from 50% body weight to 0% body weight, indicating that a single postural adjustment was made to unload the stepping leg. The second profile had two postural adjustments prior to liftoff, with the stepping leg initially loading to propel the center of mass toward the stance leg, followed by the VGRF decreasing to unload the stepping leg so that the step could be taken.

The proportion of trials in which older subjects displayed one postural adjustment formed a relatively continuous distribution from 100% to 0% (Figure 2). The bulk of the remaining trials had two postural adjustments. In a few cases, additional reversal points in the VGRF were observed, even though the subject stepped with the correct leg. In order to further explore the characteristics of these stepping strategies, we divided the older sample into 3 groups of subjects. Subjects who had a preferred strategy of stepping with one PA were assigned to Group ONE, subjects who had a preferred strategy of generating two PAs were assigned to Group TWO, and the remainder of the subjects was assigned to Group MIXED. The mean and range of the percentage of stepping trials in which subjects made one PA appears in Table 1. The three groups did not differ in gender composition or age (Table 1). By comparison, 18 of the 20 younger adult subjects had a single PA in over 94% of the step trials. The remaining 2 younger adult subjects had a single PA in over 77 and 79% of the step trials. The proportion of subjects who had a single PA differed between younger and older adults ($\chi^2 = 19.7$, $p < 0.001$).

Latency of postural adjustments

There was a significant effect of older adult group membership on the latency of PA₁ ($F_{2,67} = 5.70$, $p = 0.005$, Table 2). Group MIXED had a delay in PA₁ of approximately 40 ms compared with Groups ONE and TWO ($p < 0.03$). Because Group MIXED did not have a preferred stepping postural strategy, we examined if the latency of the trials with one PA differed from the latency of the trials with two PA within Group MIXED. The latency of PA₁ for Group MIXED was significantly greater during the stepping trials with one PA compared with two PAs (paired $t_{23} = 3.6$, $p = 0.002$). Consequently, two sub-analyses were performed: Group ONE v. Group MIXED for trials with one PA only, and Group TWO v. Group MIXED for trials with two PAs only. For trials with one PA, Group MIXED PA₁ was significantly delayed by 62 ms compared with Group ONE (t_{45} , $p < 0.001$). However Group MIXED PA₁ obtained from trials with two PAs was not significantly delayed compared with Group TWO (t_{45} , $p = 0.084$).

The liftoff (LO) was significantly different among the groups ($F_{2,67} = 25.0$; $p < 0.001$, Table 3). Group ONE had the earliest LO, followed by Group MIXED, then Group TWO (all Tukey pairwise differences had $p < 0.002$). This result reflects the increase in LO due to two PAs compared with one. After partitioning the trials of Group MIXED into one and two

postural adjustments, the LO latencies continued to be significantly different from those of Group ONE and Group TWO, respectively. It is interesting that even though Group MIXED had a slightly delayed PA₁ latency compared with Group TWO, the LO of Group MIXED occurred significantly earlier than Group TWO. This can be explained by a significantly smaller change in push-off force ($t_{30,1} = 3.8$, $p = 0.001$) between PA₁ and PA₂ for Group MIXED (3 ± 2 % body weight) compared with Group TWO (7 ± 4 % body weight)

Stepping behavior and fall risk

Subjects in Group TWO had greater frequency of falls (39%) compared with Group ONE (17%) and Group MIXED (17%). Logistic regression was used to determine if a significant relationship existed between a history of falling in the past year and the measures of step behavior. An increase in latency of the liftoff (Wald statistic = 4.5, $\beta = 0.602$, $p = 0.035$), and greater proportion of trials with two postural adjustments (Wald statistic = 4.7, $\beta = 0.653$, $p = 0.030$), were both significant predictors of a fall history in the past year. The odds ratio for a one standard deviation (123 ms) increase in liftoff latency was 1.83 (95% CI: 1.04 – 3.19). The odds ratio for a one standard deviation (39%) increase in proportion of steps with two postural adjustments was 1.92 (95% CI: 1.06 – 3.47). Models were not substantially improved by the addition of age and gender as covariates.

Discussion

Stepping behavior

While younger adults consistently demonstrated use of one postural adjustment, the proportion of trials in which older subjects made a single postural adjustment ranged from 0 to 100%, with the bulk of the remaining steps showing two postural adjustments. Thus, there appears to be an impact of aging on some adults that leads to two postural adjustments to initiate stepping. In addition, there is evidence to suggest that the number of postural adjustments made and latency of foot liftoff are related to a history of past falls.

Although the observation of both postural adjustment strategies was previously reported in the study of Patla et al., the relative frequency of this step behavior was not reported for younger or older adults until now.⁵ These behaviors seen in our study of older adults may be associated with factors related to biological aging, as the sample of younger adults rarely displayed this behavior. Clearly, stepping with one postural adjustment results in a faster foot liftoff and step completion, which was the stated goal in this experiment. More postural adjustments result in a later liftoff and subsequently a delayed step. Therefore, the rationale for increasing the number of postural adjustments is counter to the instructed goal. The reason for subjects using two postural adjustments may be to increase stability during the step. From a biomechanical perspective, using two postural adjustments initially moves the center of gravity toward the stance foot. This may then allow the step to be performed with the center of mass in a more stable initial position (i.e. closer to the base of support while the stepping leg is not in contact with the ground). This strategy makes sense if a person does not have the muscle power to quickly abduct the leg ahead of a laterally falling center of mass. Note that there was no difference in age among the 3 groups that had different step behaviors, so chronological age does not account for the selection of step behavior.

Variation in the control of lateral postural reactions during stepping appears to be an indicator of aging. Whereas voluntary lateral stepping has not been explored in much detail, perturbed lateral and forward stepping provide supporting evidence of this assertion. In response to forward, backward, and lateral perturbations that induced compensatory steps, older adults more frequently took additional steps, had limb collisions, and had arm reactions, so as to maintain stability in the lateral direction.^{2, 3, 9, 10} It has been suggested

that difficulties with hip abduction power and lateral trunk control are responsible for these changes in lateral stability with aging.³ A related finding of differences in stepping strategy during recovery from release of a tethered forward lean was reported by Carty et al.^{11, 12} In these experiments, older adults demonstrated both single and multiple step recoveries. Multiple step recoveries were related to less lower extremity power and hip strength.^{11, 12}

Subjects in Group MIXED did not have a preferred strategy for one or two postural adjustments. In 15 of these subjects, the step behavior depended on the direction of step, perhaps reflecting some asymmetry in their neuromuscular function. Three of the MIXED subjects had approximately equal number of steps with one or two postural adjustments, and no direction preference was observed. Perhaps these subjects are in a state of transition from a step behavior of one to two postural adjustments.

Latency of postural adjustments

The impact of the step behavior on the liftoff latency is clear. Subjects who use two postural adjustments have a longer latency of LO, accounting for a 200 ms difference between LO times for Group TWO compared with Group ONE. Hence the ability of subjects in Group TWO to take a step in order to prevent a fall should be compromised compared with Group ONE. This is supported by studies showing that greater step initiation times are evident in older adults with balance impairments and higher falls risk.^{13–15}

Analysis of the Group MIXED LO times, stratified by one or two postural adjustments, reveals several other interesting insights. Group MIXED also has a significantly greater liftoff time compared with Group ONE, by 81 ms. Most of this difference is due to the delayed PA₁ (62 ms), but there is also a greater weight transfer time, i.e. the difference between the latency of LO and PA₁, of 19 ms. Comparison of Groups TWO and MIXED tell a different story. Considering only the steps with two postural adjustments, Group TWO has an earlier initial postural adjustment compared with Group MIXED (32 ms). Despite this advantage, the liftoff time of Group TWO is delayed by 69 ms compared with Group MIXED. Thus, Group TWO has a longer weight transfer time of about 100 ms, due principally to generating a larger push-off force with the stepping leg. The size of the push-off force determines how far the center of mass translates toward the stance leg. Consequently, the larger push-off force in Group TWO would be more stable biomechanically, but have a more detrimental effect on their ability to respond quickly with a protective step.

Stepping behavior and history of falls

In order to examine potential real world consequences of these stepping behaviors, subjects were asked to recall if they had fallen in the past year. Subjects who used two postural adjustments, and had longer LO latencies, had a greater likelihood of reporting a fall in the previous year. These findings are consistent with a previous report showing that disordered control of the lateral movement of center of mass and foot placement is related to a history of falls.⁴ One hypothesis is that many subjects who fall have some underlying instability, and that instability is also underlying the more conservative stepping behavior that was observed in Group TWO. In addition, it is possible that once a person has fallen, their activity level decreases, resulting in less muscle strength and adoption of a more conservative strategy. Given the hypothesized increased biomechanical stability gained by stepping with two postural adjustments, this behavior may be used to compensate for reduced motor control or muscle power during these whole body movements.

If older adults with have a disadvantaged step behavior, or delayed step initiation, they could be enrolled in an intervention program to try to improve the biomechanics or speed of step

initiation. For instance, the group of Rogers et al. has demonstrated that step-training interventions improved step initiation times and stepping strategies in older adults.^{16, 17} Thus identification of these abilities using a relatively simple task could lead to targeted rehabilitation protocols.

The current results are necessarily preliminary. Self-report data on falls were obtained, but either observational or experimental data on fall susceptibility was unavailable. The results do suggest though that older adults may adapt to aging losses by altering their lateral stepping behavior, and that particular lateral stepping behavior may be related to falls.

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Research Highlights

- Older adults demonstrate 2 main strategies for voluntary lateral step initiation.
- One or two postural adjustments in the loading of the stepping limb are seen.
- Younger adults consistently step laterally using only one postural adjustment.
- Production of 2 postural adjustments is associated with a fall in the past year.
- Longer foot liftoff latency is associated with a fall in the past year.

Figure 1.

Representative vertical ground reaction force (VGRF) curves for lateral steps that had 1 and 2 postural adjustments. PA₁ marks the first postural adjustment, PA₂ is the second postural adjustment, and LO is the time of liftoff.

Figure 2.

The percentage of trials in which subjects made one postural adjustment (PA). The descriptive statistics for younger adults are demonstrated by the rectangle (25th to 75th percentile), horizontal line (median) and stars (extreme values). The individual values for the older subjects are represented by the open circles.

Table 1

Group Characteristics.

	Group ONE	Group TWO	Group MIXED	p-value
N	23	23	24	
Percentage of trials with one postural adjustment	97 (3) Range 89 – 100	5 (7) Range 0 – 24	58 (129) Range 29 – 88	< 0.001
Gender (males, females)	13, 10	6, 17	10, 14	0.11
Age (years)	75 (4)	77 (6)	76 (4)	0.48

Table 2

Mean latency (SD) of the first postural adjustment (PA₁) for the three groups.

	Group ONE	Group TWO	Group MIXED	p-value
PA ₁ (ms) all steps	238 (43)	230 (53)	275 (51)	Overall 0.005
PA ₁ (ms) one postural adjustment only	239 (45)		301 (62)	ONE v. MIXED < 0.001
PA ₁ (ms) two postural adjustments only		226 (51)	258 (70)	TWO v. MIXED 0.084

Table 3

Mean latency (SD) of the liftoff (LO) for the three groups.

	Group ONE	Group TWO	Group MIXED	p-value
LO (ms) all steps	444 (63)	641 (125)	544 (85)	Overall < 0.001
LO (ms) one postural adjustment only	443 (63)		524 (84)	ONE v. MIXED 0.001
LO (ms) two postural adjustments only		643 (123)	574 (95)	TWO v. MIXED 0.038