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Lateral Stability During Forward-Induced Stepping for Dynamic Balance Recovery in Young and Older Adults

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Background. Balance dysfunction related to lateral instability has been associated with falls and fall-related injuries among older individuals. Protective stepping for dynamic balance recovery requires the effective control of lateral body motion. This study investigated the relationship between aging, falls, and lateral stability during forward-induced stepping for dynamic balance recovery.

Methods. Forward steps were induced by a motor-driven waist-pull system in 12 younger adults, 20 healthy community-dwelling older adult nonfallers, and 18 older adults who had reported falls. Group differences in kinetic and kinematic stepping characteristics for a range of postural disturbance magnitudes were evaluated.

Results. Despite group similarities in anticipatory postural adjustments for minimizing lateral instability, the older fallers demonstrated significantly greater sideways body motion toward the stepping side at first-step foot contact and a more laterally directed foot placement. During the first step, forward-stepping characteristics were generally comparable between the groups, but the older fallers had an earlier liftoff time and longer step duration.

Conclusions. During forward-induced protective stepping, otherwise healthy older adults who had experienced falls showed particular differences in their control of lateral body motion that were not attributable to changes in anticipatory postural mechanisms. Aging changes in controlling lateral body motion during protective stepping appear to involve factors that intervene between the first-step liftoff and foot contact and/or adaptations in stepping patterns related to prior planning.

AN increased susceptibility to falling is one of the major problems associated with human aging. Functional changes in posture, balance, and gait have been commonly associated with an increased risk of falling among older adults (1–5). From a balance control perspective, the effective performance of such functional activities is critically dependent upon an individual's ability to adequately regulate the relationship between the body center of mass (COM) and the base of support (BOS).

A growing body of evidence (6–11) has emphasized that strategies that involve active changes in the BOS relative to the COM, such as stepping or grabbing, are commonly executed protective behaviors for maintaining balance in the everyday environment. Stepping may be initiated volitionally as protection against a fall or induced reactively whenever the COM–BOS relationship is disrupted by external means.

A common functional requirement of stepping is the lateral transfer of body weight support. During stationary bipedal standing, the medio-lateral (M-L) COM position is generally centered above the BOS area between the feet (Figure 1A). Lifting one foot markedly reduces the BOS to the area of the single supporting foot (Figure 1B). Without postural corrections, the body would abruptly begin to fall toward the unsupported side. For volitional leg movements (12–14), anticipatory postural adjustments (APAs) propel the COM toward the single support side prior to lifting the limb, thereby minimizing the tendency for the body to fall laterally at liftoff (Figures 1C and 1D). In contrast to volitional movements, APAs are often absent or diminished in effectiveness during externally induced protective stepping (8,15,16), and this appears to compromise M-L stability (16).

An impaired ability to maintain lateral stability during protective stepping may be particularly relevant to the problem of falling among older people. For example, measures of M-L stability are well associated with future (17) and past (18) falls. Moreover, epidemiological studies (19–21) have indicated that falls most often involve lateral body motion, and hip fractures are most commonly associated with lateral falls. To date, only a very limited number of studies (15,22,23) have investigated the abilities of older adults to control lateral body motion during dynamic balance recovery through stepping.

The present study investigated whether the operational characteristics of protective stepping for balance recovery are altered in relation to age and history of falling. We hypothesized that otherwise healthy community-dwelling older persons in general, and elderly persons who had recently experienced falls in particular, would demonstrate differences in their stepping performance related to controlling lateral body motion when steps were induced by differ-

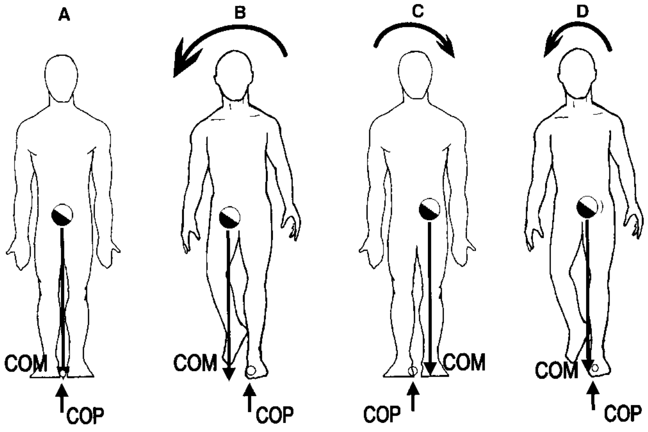

Figure 1. Conceptual scheme of the lateral postural control problem during the transition from standing to stepping. **A**. During stationary standing with the weight equally distributed between the legs, the vertical projection of the body center of mass (COM, larger half-filled circle) to the support surface approximates the location of the center of pressure (COP) distributed beneath the feet (small open circle) such that standing equilibrium is achieved. **B**. If one leg is abruptly raised from the ground to take a step and no postural compensation has occurred, then the COM and COP would be located at a distance from one another and the body would fall laterally and downward toward the unsupported side. **C**. Medio-lateral anticipatory postural adjustments (M-L APAs) minimize potential instability via an initial shift of the COP to the right step side that propels the COM toward the left single support leg prior to leg liftoff. **D**. When the leg is lifted following the M-L APA, the COM is located closer to the new COP point of support, and a sideways fall is minimized.

ent magnitudes of forward waist-pull disturbances of standing balance.

METHODS

Subjects

A total of 50 subjects participated in the study. Twelve healthy adults (9 women, 3 men) aged 23 years to 43 years (mean ± *SD*, 31 ± 7 years) comprised the younger adult group. Thirty-eight community-dwelling healthy older adults (32 women, 6 men) at least 60 years of age were recruited as volunteers through an Aging Research Registry and Geriatric Evaluation Service. Prior to testing, all subjects provided written informed consent to participate in the study.

Elderly subjects were evaluated by a physician geriatrician to screen for exclusion criteria that included neurological, musculoskeletal, cardiovascular, pulmonary, cognitive, functional capacity, and other systemic conditions as well as medication use. On the basis of each individual's self-reported history during the 12 months prior to assessment, the older subjects were classified into two separate groups (Table 1) as either recent fallers (one or more falls, $n = 18$) or nonfallers ($n = 20$). A fall was defined as "an event which results in a person coming to rest inadvertently on the ground or other lower level regardless of whether an injury was sustained, and not as a result of a major intrinsic event or overwhelming hazard" (18 [p. 1078], 24 [p. 1702]). An overwhelming hazard was defined as "a hazard that would result in a fall by most young, healthy persons" (24) as determined by a consensus of at least three of the investigators.

Table 1. Subject Characteristics

Parameter	Young Adults ($n = 12$)	Nonfallers ($n = 20$)	Fallers ($n = 18$)
Age, y	31 (7)	71 (5)	74 (8)
Height, m*	1.68 (0.06)	1.63 (0.10)	1.63 (0.06)
Mass, kg	60.1 (5.7)	63.5 (14)	65.4 (13.6)

Note: Values are means with standard deviations in parentheses.
*Significant (*t* test: $p < .05$) difference between young adults and fallers.

Experimental Protocol and Data Collection

A schematic diagram of the experimental setup is shown in Figure 2. Subjects stood on two separate force platforms (Advanced Mechanical Technology, Newton, MA) using a standardized foot position. An online visual display controlled the initial postural weight-bearing conditions prior to each trial. Stepping kinematics were recorded using a two-camera video-based motion analysis system (Peak Performance, Englewood, CO) that registered the motion of reflective markers placed over standard body landmarks (25). Data were digitally sampled at 120 Hz for 5 seconds during each trial.

Induced forward stepping was evoked by a motor-driven waist-pull system (26). A flexible cable was attached at one end to the puller and at the other end to a rigid connection aligned with the umbilicus on a waist belt. Five different magnitude combinations of pulling displacement, velocity, and acceleration were applied: P1 = 4.5 cm, 9 cm/s, 180 cm/s/s; P2 = 9 cm, 18 cm/s, 360 cm/s/s; P3 = 13.5 cm, 27 cm/s, 540 cm/s/s; P4 = 18 cm, 36 cm/s, 720 cm/s/s; and P5 = 22.5 cm, 45 cm/s, 900 cm/s/s. A safety harness prevented injury but did not restrict movement. Subjects were instructed to "react naturally to prevent themselves from fall-

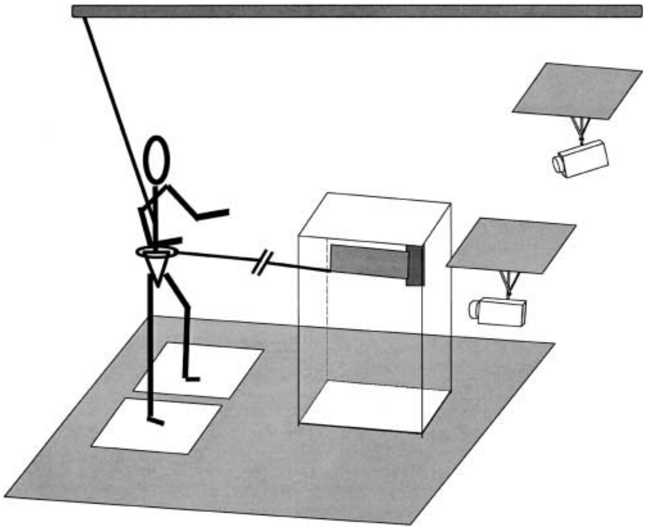

Figure 2. Schematic diagram of the experimental setup showing a subject standing on the force platforms facing motion capture cameras and attached to a safety harness while awaiting a forward waist-pull postural perturbation. Modified from reference 10.

ing" in response to the pulls. Following one practice trial each at P1, P3, and P5, blocks of three trials at each of the five levels of pulling magnitude were randomly performed.

Data Analysis

Interactive graphical analysis programs were used to compute the outcome measures for each trial. The onset of the waist-pull displacement was specified as time zero for determining onset-timing variables. The first-step liftoff time was identified when the vertical force was reduced to zero for that leg. M-L APAs included the presence of a bilaterally asymmetric step-limb loading/stance-limb unloading force pattern with an initial shift in the M-L center of pressure (COP) toward the step limb. Identified APAs were characterized by three kinetic variables: onset timing, peak amplitude, and duration. A statistically based algorithm (12) automatically estimated the instant of onset for kinetic and kinematic (see below) variables. The APA amplitude was computed as the maximum step side M-L COP displacement from baseline, and the duration was the elapsed time to the peak amplitude.

The first step kinematics were derived from the linear motion of the foot (second toe) marker. A nine-segment model (feet, shanks, thighs, arms, and head-trunk) estimated COM motion on the basis of known segment parameters (25). The variables computed to characterize stepping included antero-posterior (A-P) step distance, M-L foot placement, step duration, COM displacement, and COM velocity. The first-step distances were measured from the starting position through the maximum displacement at foot contact (see Figure 3). Step duration was the time to complete the first step. A-P and M-L COM displacements with respect to baseline were computed for the instants of the first foot liftoff and foot contact. Differentiation of the position data was applied to determine the COM velocity.

Statistical Analysis

The group mean differences in the dependent variables were assessed using an ANOVA for repeated measures on the within-subjects factor magnitude of waist pull. In cases of significance, paired contrast analyses were applied. Due to between-group differences in height (see Table 1), distance measurements were expressed as a proportion of individual subject height. Pearson correlations for all trials with steps determined the associations between aspects of stepping performance (i.e., step duration, M-L foot placement) and M-L COM characteristics. A significance level of $p \leq .05$ was used for all comparisons.

RESULTS

Across the groups, the occurrence of stepping and the number of steps per trial in each magnitude condition increased between the smallest (P1) and the largest (P5) pulls. For the analyses that follow, the stepping characteristics were evaluated for pull levels P3 through P5 where all subjects stepped in all trials. Technical problems resulted in a total of nine missing trials involving three older subjects. Because the repeated measures ANOVA requires that all dependent measures be present in all subjects for inclusion, the absence of responses was treated as missing data. For all ANOVA comparisons, no significant ($p > .05$) interaction between group and pull level was observed.

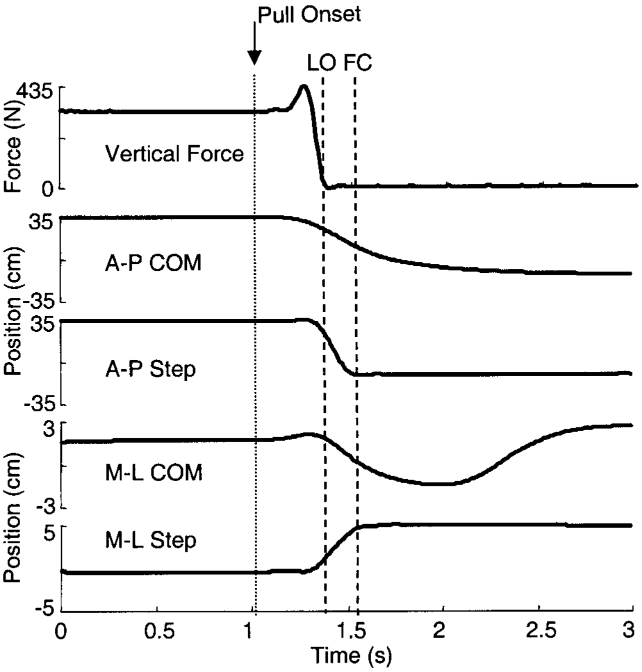

Figure 3. Representative example of an induced stepping trial during a forward waist pull in a younger subject. The dotted vertical line marks the instant of the pull onset. The vertical force beneath the first step limb records the instant of foot liftoff (LO) marked by the first broken vertical line. Kinematic records show the antero-posterior (A-P) and medio-lateral (M-L) displacement of the first step foot and the center of mass (COM). The second broken vertical line marks the time of the first-step foot contact (FC) as determined by the A-P step position–time history. Negative step and COM values indicate motion forward and toward the step side. Other abbreviations are as in Figure 1.

Prior to stepping, M-L APAs occurred in 66% of all trials with steps for the younger group, 64% for the nonfallers, and 59% for the fallers. For the P3 through P5 trials with APAs, the onset time (young = 210 ± 20 ms [mean ± *SEM*]; nonfallers = 240 ± 10 ms; and fallers = 210 ± 10 ms), and duration (young = 140 ± 10 ms; nonfallers = 130 ± 10 ms; and fallers = 120 ± 10 ms) of responses were similar (*t* test: $p > .05$) among the groups. There was a tendency for the older subjects to produce larger peak amplitudes of APAs (nonfallers = 3.7 ± 0.4 cm; fallers = 3.8 ± 0.4 cm) than the younger subjects (2.7 ± 0.4 cm), but this trend was not statistically significant (*t* test: $p > .05$).

The first-step liftoff time differed among the groups (main effect: $p < .05$) with the fallers responding sooner than the nonfallers (post hoc: $p < .01$) and the young adults (post hoc: $p < .05$). For pulling magnitudes P3 through P5, the onset of stepping became progressively earlier (main effect pull condition: $p < .001$) with increasing pulling magnitude (Table 2).

As summarized in Table 2, there were no significant differences (main effect: $p > .05$) among the groups in the forward COM displacement and velocity and step length at foot contact. As the pulling magnitude became larger, the

Table 2. First-Step Characteristics for Different Magnitudes of Waist Pull

	Pull Magnitude		
	P3	P4	P5
Liftoff Time, s*†			
Young adult	0.560 (0.04)	0.460 (0.03)	0.410 (0.03)
Nonfaller	0.510 (0.03)	0.440 (0.02)	0.390 (0.01)
Faller	0.420 (0.01)	0.360 (0.01)	0.340 (0.01)
A-P Step (distance [m]/height [m])†			
Young adult	0.230 (0.02)	0.285 (0.01)	0.330 (0.02)
Nonfaller	0.272 (0.02)	0.300 (0.01)	0.324 (0.02)
Faller	0.287 (0.02)	0.300 (0.01)	0.324 (0.02)
Step Duration, s*			
Young adult	0.310 (0.01)	0.330 (0.01)	0.330 (0.01)
Nonfaller	0.350 (0.01)	0.340 (0.01)	0.330 (0.01)
Faller	0.370 (0.01)	0.360 (0.01)	0.350 (0.01)
A-P COM (distance [m]/height [m])†			
Young adult	0.142 (0.01)	0.172 (0.01)	0.209 (0.01)
Nonfaller	0.157 (0.01)	0.181 (0.01)	0.203 (0.01)
Faller	0.151 (0.01)	0.169 (0.01)	0.198 (0.01)
A-P COM (velocity [m/s]/height [m])†			
Young adult	0.327 (0.02)	0.436 (0.01)	0.549 (0.02)
Nonfaller	0.384 (0.02)	0.486 (0.02)	0.578 (0.02)
Faller	0.400 (0.02)	0.495 (0.02)	0.599 (0.02)

Notes: A-P = anterio-posterior; COM = center of mass. Values are means with standard errors in parentheses.

*Significant difference between groups.

†Significant main effect for pull magnitude condition.

step length concomitantly increased (main effect pull condition: $p < .001$) with increases in forward COM displacement (main effect pull condition: $p < .001$) and velocity (main effect pull condition: $p < .001$). A main effect for group ($p < .05$) indicated that the fallers had a greater overall step duration than the younger adults (post hoc: $p < .01$). Collapsing across the groups, the step duration was unchanged (main effect: $p > .05$) in relation to the magnitude of waist pull.

At first step liftoff, the M-L COM displacement and velocity were similar (main effect: $p > .05$) among the groups (Figures 4A and 4C). As the magnitude of the waist pull increased, the COM was displaced further toward the first-step side (main effect: $p < .001$; all post-hoc comparisons $p < .05$). In contrast, at foot contact (Figures 4B and 4D), the groups differed significantly for M-L COM displacement (main effect: $p < .02$), velocity (main effect: $p < .001$), and M-L foot placement (main effect: $p < .001$) (Figure 5). The fallers displayed greater COM displacement (post-hoc: vs young adults, $p < .01$; vs nonfallers, $p < .02$), and velocity (post-hoc: vs young adults and vs nonfallers, $p < .01$), and a more laterally directed foot placement (post-hoc: vs young adults and vs nonfallers, $p < .001$) (Figure 5). Across the groups, neither M-L foot placement nor M-L COM motion varied in relation to the magnitude of the waist pull (main effect: $p > .05$).

For each group, there were similarly significant ($p < .05$) associations between M-L foot placement and COM displacement (young adults: $r = .57$, $r^2 = .33$; nonfallers: $r = .84$, $r^2 = .70$; fallers: $r = .76$, $r^2 = .57$) and velocity (young adults: $r = .61$, $r^2 = .37$; nonfallers: $r = .68$, $r^2 = .47$; fallers: $r = .69$, $r^2 = .48$). Trials in which the M-L COM was displaced closer to the stance-limb side with smaller velocities toward the step-limb side were associated with a more medially directed foot placement toward the mid-sagittal line. Lower but significant ($p < .05$) associations were also found between first-step duration and the M-L COM displacement (young adults: $r = .20$, $r^2 = .04$; nonfallers: $r = .13$, $r^2 = .02$, $p = .10$; fallers: $r = .32$, $r^2 = .10$) and velocity (young adults: $r = .27$, $r^2 = .07$; nonfallers: $r = .17$, $r^2 = .03$; fallers: $r = .33$, $r^2 = .11$) at foot contact. As stepping duration increased, the M-L COM motion toward the step limb side tended to increase.

Discussion

This study demonstrated that, compared with younger adults and healthy older adult nonfallers, older individuals who reported a recent history of falling had increased lateral body motion at first-step foot contact that was associated with a more lateral foot placement. These differences were not attributable to alterations in anticipatory postural mechanisms for preserving lateral stability but appeared to involve factors related to the ongoing control of M-L body motion between first-step liftoff and foot contact and/or differences in stepping strategies possibly reflecting prior planning. Despite generally similar forward-stepping characteristics among the groups, the fallers had a greater first-step duration time compared with the young adults, and this was associated with the extent of lateral COM motion at foot contact.

Our findings indicate that the previously reported (15,16) diminution in M-L APA characteristics during compensatory protective stepping compared with volitional stepping is equivalent among younger and older individuals, including elderly fallers. This similarity led to comparable M-L COM motion at the time of foot liftoff. Therefore, it is unlikely that aging differences in controlling lateral stability during stepping are attributable to differences in anticipatory postural mechanisms related to weight transfer.

Interestingly, the liftoff time was earliest for the fallers. This result might have been related to preplanning to step if older subjects had perceived stepping as a more secure balance strategy. The known direction of the postural challenge could have facilitated the adoption of a default stepping solution and earlier initiation times. Another possibility may be that the earlier step taken by the fallers reflected greater instability associated with the forward fall. The generally comparable reaction times for induced stepping between young adults and old adults (27) is in contrast to the age-associated delays in volitional stepping tasks (27,28) and might reflect fundamental differences in the effects of human aging on volitional versus “reflex-like” step initiation. This difference underscores the need to assess both forms of stepping performance with respect to balance function and falls (27).

All subjects similarly adapted their forward step length to match their comparable forward body motion during the initial step. In contrast, however, the fallers had a longer first-step duration than the younger group. The greater step duration resembled a past observation of limitations in the maximum stepping speeds at which older adults could recover balance (9) and could increase the risk of falling in such time-critical situations. Moreover, because step duration

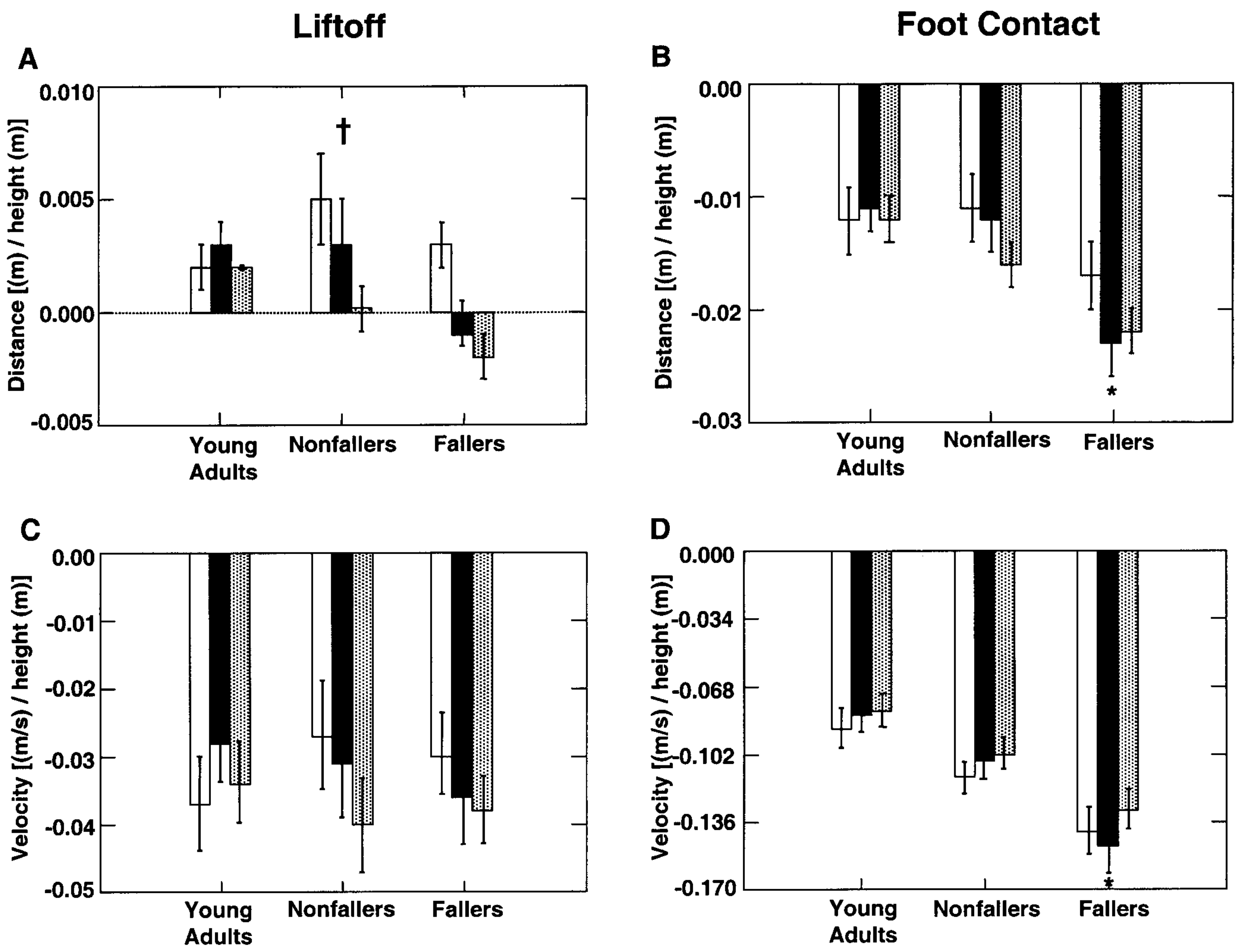

Figure 4. Group mean values ± 1 *SEM* for medio-lateral center of mass (M-L COM) displacement, **A** and **B**, and velocity, **C** and **D**, at the instants of first-step liftoff and foot contact during forward-induced stepping at small (P3), medium (P4), and large (P5) waist-pulls. Negative values are in the direction of the stepping side. *Indicates a significant difference ($p < .02$) between fallers versus nonfallers and young adults. †Indicates a significant difference ($p < .01$) between pulling magnitude conditions. □ P3; ■ P4; ▨ P5.

time was associated with M-L body motion, the longer time spent in single-limb support for the fallers also allowed a greater period of time for subjects to fall sideways.

By foot contact, the fallers had fallen farther sideways with greater velocity and lateral foot placement. The associations between M-L COM motion and foot placement suggested that stepping was adapted to match the lateral movement of the COM. Possibly, the fallers included a wider step to compensate for the instability that developed between liftoff and foot contact. In contrast, the nonfallers and younger subjects stepped toward the mid-sagittal line of forward progression in a manner similar to that of ongoing locomotion (29). Because the direction of destabilization was known in advance, the fallers might have preplanned a lateral foot placement to compensate for M-L instability and/or anxiety about falling. It is also possible that the lateral foot placement could have induced the M-L body motion observed. A past study (22) of older nonfallers did not observe aging differences in first step M-L foot placement for directionally uncertain A-P platform translations. However, active and healthy older adults may have difficulties in controlling lateral stepping reactions (23). Alternatively, aging changes in ongoing postural stabilization of the single support limb (30) and/or deficits in vestibular-mediated responses for M-L head/body control (31) might have contributed to our observations.

It is acknowledged that, because falling was recorded retrospectively, the true occurrence of falls might have been underestimated due to limited recall accuracy. Furthermore, the differences in M-L stepping behavior in the fallers may have been influenced by their history of falling. However, rather strong associations have been found between past falls and future falls (1,2,24), so that the differences in controlling M-L body motion found here are likely to have implications for subsequent falls. Finally, the present findings are consistent with information from a prospective study of 100 community-dwelling older persons (17) in which measures of M-L stability were the best predictors of falls.

In summary, during dynamic balance recovery through forward-induced stepping, otherwise healthy older individu-

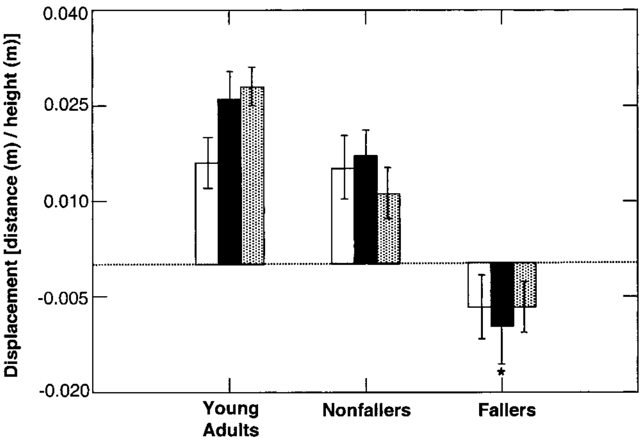

Figure 5. Group mean values ± 1 *SEM* for medio-lateral (M-L) foot placement at the instant of the first-step foot contact during forward-induced stepping at small (P3), medium (P4), and large (P5) waist pulls. Positive values indicate motion toward the mid-sagittal line of the body. *Indicates a significant difference ($p < .001$) between fallers versus nonfallers and young adults. □ P3; ■ P4; ▨ P5.

als who reported a recent history of falling moved more laterally more quickly at the completion of the first step than younger and older adult nonfallers. This difference in lateral stepping behavior was not attributable to changes in anticipatory postural mechanisms but appeared to involve factors associated with the subsequent compensatory stepping movement and/or differences in response strategies related to prior planning. The results highlight the association between falling in older people and particular changes in controlling lateral body motion during dynamic balance recovery through stepping. Our ongoing studies are seeking to further identify the impairments contributing to lateral balance dysfunction to specify rehabilitation interventions for minimizing the incidence of falls among older individuals.

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