Age-related Changes in Compensatory Stepping in Response to Unpredictable Perturbations

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Background. Recent studies highlight the importance of compensatory stepping to preserve stability, and the spatial and temporal demands placed on the control of this reaction. Age-related changes in the control of stepping could greatly influence the risk of falling. The present study compares, in healthy elderly and young adults, the characteristics of compensatory stepping responses to unpredictable postural perturbations.

Methods. A moving platform was used to unpredictably perturb the upright stance of 14 naive, active and mobile subjects (5 aged 22 to 28 and 9 aged 65 to 81). The first 10 randomized trials (5 forward and 5 backward) were evaluated to allow a focus on reactions to relatively novel perturbations. The behavior of the subjects was not constrained. Forceplate and kinematic measures were used to evaluate the responses evoked by the brief (600 msec) platform translation.

Results. Subjects stepped in 98% of the trials. Although the elderly were less likely to execute a lateral anticipatory postural adjustment prior to foot-lift, the onset of swing-leg unloading tended to begin at the same time in the two age groups. There was remarkable similarity between the young and elderly in many other characteristics of the first step of the response. In spite of this similarity, the elderly subjects were twice as likely to take additional steps to regain stability (63% of trials for elderly). Moreover, in elderly subjects, the additional steps were often directed so as to preserve lateral stability, whereas the young rarely showed this tendency.

Conclusions. Given the functional significance of base-of-support changes as a strategy for preserving stability and the age-related differences presently revealed, assessment of the capacity to preserve stability against unpredictable perturbation, and specific measures such as the occurrence or placement of multiple steps, may prove to be a significant predictor of falling risk and an important outcome in evaluating or developing intervention strategies to prevent falls.

The prevalence and consequences of falls in the elderly have led to research to identify the factors that contribute to age-related changes in postural stability. Most studies have evaluated tasks requiring the control of the center of mass (COM) over a stationary base of support (BOS), i.e., standing with feet kept in place. However, the challenges to balance during everyday life are often likely to demand rapid changes in the BOS to control stability, i.e., stepping. In fact, studies characterizing compensatory stepping responses to external perturbations have revealed that stepping is a prevalent strategy to preserve stability even when the perturbation is relatively small (1–4). Arguably, the challenge of controlling both the BOS and COM is likely to be quite distinct as compared to tasks featuring a stationary BOS.

It is known that compensatory stepping responses in young adults are initiated very quickly after the onset of perturbation (1,2). Given the evidence of age-related delay in the early "automatic" postural responses evoked by perturbation (5) and, more generally, age-related slowing of reaction times (6), it is reasonable to hypothesize that there will be delays in the initiation of compensatory stepping with increasing age. Furthermore, since compensatory stepping is normally characterized by high velocity of movement (7,8), it is possible that age-related decline in peak muscle strength (9) might also contribute to a delay in the time at which the foot contacts the ground.

Age-related slowing of the compensatory stepping response, due to changes in onset latency or movement speed, could influence stability, as the time to achieve the new BOS, as well as the placement of the swing foot, must be closely matched to the temporal and spatial features of the changes in COM imposed by the perturbation. Errors or delays in the foot placement could result in a stepping response that does not adequately capture the moving COM and therefore requires further compensatory reactions (e.g., multiple steps), and it is quite possible that an inability to generate rapid and effective compensatory BOS changes may be strongly associated with falling risk. The present study characterizes, in healthy and active elderly and young adults, the temporal and spatial characteristics of compensatory stepping in response to unpredictable perturbation, in order to determine the age-related differences in control.

Materials and Methods

Fourteen of 15 consecutively recruited volunteers participated in the study. There were 5 young subjects (22–28 years, 3 males, average weight 67 kg, average height 173 cm) and 9 elderly subjects (65–81 years, 6 males, average weight 71 kg, average height 170 cm). One elderly volunteer was excluded because of a persistent history of falling and an expressed fear of falling. Each subject signed informed consent to comply with ethics approval granted by the Research Ethics Board of the Sunnybrook Health Science Centre. In order to identify the reactions to unfamiliar perturbations, only subjects who were not familiar with postural perturbation experiments were recruited.
Information regarding the health status and activity patterns was determined by a standardized verbal questionnaire administered to the subjects by the experimenter. None of the subjects reported significant musculoskeletal problems, recent bone fractures, neurologic or sensorimotor disorders, or persistent problems with dizziness, vertigo, or unsteadiness. Four elderly subjects did report occasional arthritic symptoms, but said that these symptoms did not limit their activity. Only one subject was on prescribed medication and this was for a diagnosis of high blood pressure. All elderly subjects were active community-dwellers and did not require the use of any mobility aid. Each subject, young and elderly, reported participating in some moderate physical activity (including walking) either daily or every other day. Three elderly subjects did report having fallen within the last six months; however, these falls appeared to be related to "high-risk" activities (e.g., playing hockey). None of the subjects, young or old, reported a fear of falling and all subjects reported their balance, gait, and vision to be "good" or "very good."

Forward and backward stepping movements were evoked by anteroposterior (AP) translation of a movable platform on which the subject stood (8). Ground reaction forces were sampled (at a rate of 200 Hz) from two forceplates mounted side by side on the platform. The perturbation waveform, which was the same for all trials, comprised a 300-msec square-wave pulse of acceleration followed immediately by a 300-msec deceleration pulse. The peak acceleration was 1.5 meters/second$^2$; maximum velocity 0.45 m/s, displacement 0.135 m) for forward translations (which evoked forward sway). These waveform characteristics were selected, on the basis of prior experiments, to ensure that stepping responses were evoked in both directions, in both young and elderly subjects. For safety, the elderly subjects wore a harness during all trials (this harness was designed to prevent impact with the floor without otherwise restricting movement or providing proprioceptive cues). In addition, safety handrails were mounted around the perimeter of the platform (2 meters apart).

Subjects were provided with a demonstration of the platform motion prior to the first trial. Ten consecutive platform-translation perturbations were then presented, five forward and five backward. The direction of platform translation was randomized, and there was a variable delay between successive trials ranging from 30–45 sec. A standard initial foot position (angle of 12 degrees between the medial margins of the feet, 18 cm spacing between the heels) was used in all trials (this was the average preferred stance position recorded in 260 young and elderly subjects) (10). Subjects were instructed to hold their arms at their sides, to look straight ahead at a visual target (1 m away), and to "try to keep from falling." They were given no specific instructions regarding any other aspect of their behavior, i.e., foot motion was unconstrained. The focus on unconstrained reactions is important because there are important differences between responses that are preplanned (e.g., instructions to either encourage or discourage a stepping reaction) and those that are not constrained (1,11).

Evaluation of the statistical significance of measured differences between the young and elderly (and between perturbation directions) was achieved using a repeated-measures analysis of variance (ANOVA) ($\alpha = .05$). The dependent variables included: (a) onset latency, (b) time to foot-off, (c) time to foot-contact, (d) unloading phase duration (onset of swing-leg unloading to time of foot-off), (e) swing duration (foot-off to foot-contact), (f) step length, (g) swing velocity (step length/swing duration), and (h) COM displacement and velocity at time of foot-contact. It was necessary on two occasions to log-transform the data prior to conducting the ANOVA in order to address concerns that the assumptions underlying the ANOVA (i.e., normality of distribution, homogeneity of variance) may have been violated. It turned out, however, that the data transformation had a very modest influence on the $p$-values and, as a result, did not influence the interpretation of the analysis results.

Timing measures were defined with respect to onset of platform acceleration (0.01 m/s$^2$). The onset of stepping was defined in two ways: (a) onset of mediolateral (ML) asymmetry, and (b) onset of unloading of the swing limb. The onset of ML asymmetry was defined to be the onset of divergence of the left and right vertical ground reaction forces (divergence greater than 2% of body weight within 20 ms), similar to the approach used in previous studies (1,8). Note that the onset of swing-leg unloading is equivalent to the onset of ML asymmetry except in cases where an "anticipatory postural adjustment" (APA) precedes the unloading of the swing foot [the APA is marked by an initial increase in the vertical force on the swing foot, and is apparently associated with efforts to move the COM over the stance leg (12); see Figure 1]. Foot-off was defined to be the time when the loading on one forceplate dropped to less than 1% of body weight. Foot-contact was defined in a similar manner for steps where the foot landed on a forceplate (82% of trials); otherwise, the sudden decrease in vertical force on the stance leg was used, in combination with the video recordings, to define the time of foot-contact.

Four high-resolution cameras (shuttered at 1/500 sec) were used to record the motion of reflective markers placed on the foot (heel and first and fifth metatarsals), as well as the ankle, knee, hip, trunk, and head. The present study focused on the anteroposterior and mediolateral step length, and it was found that the step location could be determined simply and reliably by observing the position of the reflective marker on the fifth metatarsal relative to a grid marked on the platform, using one of the overhead camera views. These measures of foot placement were accurate to within 1 cm, as confirmed by comparing results for a subsample of trials that were also analyzed using commercial motion-analysis software (Peak Performance, Inc.; Englewood, CO). AP and ML COM displacement were determined by double-integrating the ground reaction shear forces (the initial COM position was determined by averaging the center of pressure during 200 msec of stationary standing immediately prior to the onset of the stimulus). This technique has been shown to be valid over the brief time intervals used in this study (13), and we confirmed this by comparing COM displacement calculated from video-based motion analysis to that determined from ground reaction forces, for a sub-
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sample of the trials. Figure 1 illustrates the definition of the temporal step parameters.

RESULTS

The platform perturbations consistently resulted in stepping responses in both the young and elderly. Overall, 98% of the trials featured at least one step, while 49% of the trials featured two or more steps (multiple stepping).

The temporal characteristics of the initial step of the response to perturbation were remarkably similar in the young and elderly (Figure 2). On average, the time to lift the foot off the ground differed by less than 1 msec, and the overall time to place the foot on the ground differed by only about 10 msec. The only temporal parameter that showed a statistically significant age-related difference was the onset of ML asymmetry, with a shorter latency occurring in the young subjects (198 msec vs 241 msec; $F(1,11) = 5.1, p = .04$). In contrast, the onset of swing-limb unloading was very similar in the young and elderly (273 msec vs 277 msec $F(1,11) = .02, p = .9$). An "anticipatory postural adjustment" (i.e., increase in swing-limb loading) preceded the onset of swing-limb unloading in a number of trials, and created a discrepancy of 30 to 100 msec between onset of ML asymmetry and onset of swing-leg unloading. The anticipatory adjustments occurred more frequently in the young subjects (72% of trials, vs 45% of trials in the elderly), and this difference could explain why an age-related effect was observed in one onset measure (onset of ML asymmetry) but not in the other (onset of swing-leg unloading). Indeed, the magnitude of the age-related difference seen in the onset of ML asymmetry was attenuated when the trials that exhibited an anticipatory postural adjustment were excluded from the analysis [$F(1,11) = .88, p = .4$]. (None of the findings pertaining to the other step parameters was significantly affected by the exclusion of these trials.)

The time required to unload the swing foot (measured from the onset of unloading until foot-off) was very similar between the young and elderly (126 msec vs 122 msec; $F(1,11) = 0.2, p = .7$). The peak rate of swing-limb unloading was also very similar between the two age groups (average peak unloading rates were 15 N/s and 14 N/s for young and old, respectively). Both age groups also showed similar rates of foot movement, in terms of swing duration (118 msec for the young and 133 msec for the elderly) and average swing velocity (2.5 m/s for the young and 2.2 m/s for the elderly).

Age-related differences in the spatial characteristics of the first step were also very modest, with mean differences in step length of less than 3 cm and 1 cm in the AP and ML directions, respectively (Figures 3A, 3B).
Figure 3. Average spatial characteristics of the initial step of the perturbation-evoked response, for backward and forward stepping. Mean data and associated standard deviations are shown for (A) AP (anteroposterior) step length, (B) ML (mediolateral) step length, (C) AP center-of-mass (COM) displacement at foot-contact, (D) ML COM displacement at foot-contact, (E) AP COM velocity at foot-contact, and (F) ML COM velocity at foot-contact. Positive ML values indicate motion directed toward the swing-leg side. Note that different scales are used for the AP and ML measures.

displacement at time of foot-contact, relative to the starting position, was also similar for the two age groups. The differences between means were less than 0.4 cm (4%) for both forward and backward steps (Figure 3C), and the ML COM displacement, at time of foot-contact, likewise failed to show any significant age-related differences (Figure 3D). There were also no significant age-related differences with respect to the AP or ML COM velocity at time of foot-contact (Figures 3E, 3F).

In contrast to the relative similarity in many characteristics of the initial perturbation-evoked steps (up to the time of initial foot-contact), there was considerable variation between age groups when comparing the features of the subsequent steps. Multiple stepping was almost twice as common in the elderly subjects compared to the young subjects (63% vs 35% of trials). In addition, in 12 of the 90 trials (13%), the elderly subjects eventually grasped the safety handrails, suggesting that the stepping response may have been inadequate to restore equilibrium. No grasping of the handrails was observed in the young subjects. While the majority of multiple stepping in the young occurred within the first three trials, multiple stepping in the elderly appeared to be equally likely in the later trials. The elderly also appeared to be more likely to take more than one additional step. The young subjects had only four such responses (8%), whereas 21 (25%) of responses in the elderly involved more than two steps, with some responses involving four or five steps.

The multiple stepping responses were classified according to which leg was used to take the second step, i.e., “same leg” versus “alternate leg,” and the “alternate leg” reactions were further subdivided into two classes, depending on whether the second step was in the same or opposite AP direction as the first step (Figure 4). As indicated in Table 1, the most common stepping reaction for the elderly was the “same leg” multiple-step response, for backward platform translations, and the “alternate leg/same direction” response, for forward translations. Interestingly, the “same leg” reactions were almost exclusive to the elderly subjects, occurring in over 30% of trials in this age group, and featured a second step that commonly included a large lateral component (Figure 4B). Despite the fact that the platform perturbation occurred in the AP direction, the foot moved laterally as much as 28 cm during the second step. Overall, for “same leg” reactions, the average lateral placement of the second step was 12 cm from the starting foot position. Laterally directed second steps were seen in only 4 trials (8%) for the young subjects, in contrast to occurring in nearly one-third of all trials in the elderly. This difference in frequency of occurrence was highly significant (Fisher Exact Test; \( p = .001 \)).
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The present study has demonstrated profound differences in the compensatory stepping behavior of healthy young and elderly subjects, despite remarkable similarity in many characteristics of the first step of the response (up to the time of initial foot-contact). Both age groups showed very similar swing durations, swing velocities, step lengths, and changes in COM during the initial step, and the average times to onset of swing-leg unloading, to foot-off, and to foot-contact were all nearly identical in the young and elderly. The only measurable difference in the reactions, up to the time of foot-contact, was a significantly earlier onset of ML asymmetry in the young subjects. However, in spite of the similarities in the initial stepping responses, to the point of foot-contact, the elderly subjects were much more likely to take additional steps in order to regain stability. Moreover, in many of these trials, the additional steps were apparently directed so as to recover lateral stability, a tendency that was rarely observed in the young subjects. The patterns of multiple stepping seen in these healthy elderly subjects may well reflect age-related changes in the ability to control rapid movement of the BOS to preserve stability.

The present data regarding the characteristics of the first step are similar to data reported in previous studies of compensatory stepping responses in young adults (1,8,11,14–16). Contrary to our expectations, the very rapid speed of movement that occurs in young adults was also seen in the elderly subjects. This may be explained by the fact that compensatory stepping, although rapid, does not appear to require maximal muscle forces or large ranges of motion (3,4). As a result, modest age-related reduction in musculoskeletal capacity may not pose a problem in generating the movement speeds necessary for compensatory stepping.

The slightly shorter latency in the onset of ML asymmetry seen in the young subjects appeared to coincide, in part, with a greater prevalence of ML anticipatory postural adjustments. It is possible that such early activation of ML anticipatory postural adjustments may have resulted from an improved ability to rapidly discriminate the onset of perturbation, whereas the delay in response onset in the elderly may have been related to some age-related reduction in sensitivity to peripheral sensory inputs (17) and/or increase in central processing and conduction time (6,18). In fact, such delay in detecting onset of instability might account for the reduced frequency of anticipatory adjustments in the elderly, since these adjustments would tend to jeopardize safety by delaying the response even further. Alternatively, apparent differences in timing of step onset due to the presence or absence of ML anticipatory adjustments could be related to differences in the adaptive capacities of the young and elderly (19,20), since it appears that these adjustments are an adaptation that is more likely to occur with practice (16).

Although the young subjects were more likely to include an anticipatory phase, the magnitude of the anticipatory postural activity was small, in both age groups. Furthermore, it is important to note that, in spite of the greater prevalence of anticipatory postural adjustments in the young, there was no corresponding increase in lateral stability at time of foot-contact, as reflected by the ML displacement and velocity of the COM. This supports recent work which indicates that the anticipatory postural responses that

**DISCUSSION**

Despite the pronounced variation in the pattern of the multiple stepping, few differences were evident in the characteristics of the first step associated with each type of response (Table 1). One exception was the AP length of the first step of the ‘‘alternate leg/same direction’’ reaction, which was only 50–60% of the AP length of the first step measured in other trials (Figure 4C). Given the short initial step, it is not surprising that the second step with the other leg was also in the same direction. These multiple stepping responses were also characterized by the highest velocity of the AP COM at the time of foot-contact. Overall, responses featuring multiple stepping had a higher AP COM velocity at foot-contact as compared to reactions characterized by a single step. In contrast, there was little variation between the different patterns of response in terms of the average ML COM displacement or velocity at time of foot-contact.

**Figure 4.** Foot placement during the four different patterns of stepping response: (A) single-step response, (B) ‘‘same leg’’ multiple-step response, (C) ‘‘alternate leg/same direction’’ multiple-step response, and (D) ‘‘alternate leg/opposite direction’’ multiple-step response. Data are shown for all subjects (young and elderly), and the prevalence of each response type is noted in Table 1. First and second steps are shown for multiple stepping responses. Data are normalized so that all first steps are represented as a step with the right foot. Individual stepping responses to forward and backward platform translations are shown using circle and triangle symbols, respectively. For (B), the second step (with the same leg) is indicated by the filled symbols. Average stepping responses are displayed using dashed and solid lines for responses to forward and backward platform translations, respectively.

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of the measure used to represent latency, including: (a) onset of the latency of perturbation-evoked stepping was up to 100 msec shorter in elderly subjects, compared to the young. The present study did not reveal such differences regardless of the measure used to represent latency, including: (a) onset of swing-leg unloading, (b) onset of ML asymmetry, or even (c) time to foot-off. Note that the latter measure, time to foot-off, was used to denote onset latency in the study by Luchies et al. The differences between the two studies with regard to the timing of step onset could be accounted for by some major methodological differences. First, the perturbations used by Luchies et al. were predictable in direction, and identical perturbations were presented sequentially. In light of evidence that aging can affect adaptive capabilities (19,20), it is possible that some elderly subjects reached their stability limits sooner because they were less able to adapt their responses to take advantage of the predictable features of the testing paradigm. Differences in instructional set may also account for the differences in findings. Although Luchies et al. did not report the instructions given to the subjects, it appears that they may have been encouraged to resist stepping. In this situation, the elderly may step earlier than the young because they are less prepared to risk losing balance.

As mentioned, the characteristics of the stepping behavior of the young and elderly, up to the point of foot-contact, were remarkably similar. Most striking were the differences sometimes precede compensatory stepping are commonly either too brief or too small to have any significant influence on the lateral movement of the COM (21). The present findings are in contrast to the results reported, for young subjects, by Burleigh et al. (22); however, their subjects were instructed to step in response to a predictable perturbation. The ability to preplan the stepping response has been shown to lead to an increase in the incidence and magnitude of the anticipatory postural adjustments (15,16). The potent influence of task constraints and familiarity with the perturbation characteristics has led us, in the present study, to focus on unconstrained responses to more unpredictable perturbations, in order to gain an understanding of the unplanned compensatory behavior that is needed to maintain balance in the unpredictable circumstances of daily life. The observed age-related delay in the onset of ML asymmetry and the lack of difference in other timing measures contrasts the findings of Luchies et al. (3), who reported that the latency of perturbation-evoked stepping was up to 100 msec shorter in elderly subjects, compared to the young. The present study did not reveal such differences regardless of the measure used to represent latency, including: (a) onset of swing-leg unloading, (b) onset of ML asymmetry, or even (c) time to foot-off. Note that the latter measure, time to foot-off, was used to denote onset latency in the study by Luchies et al. The differences between the two studies with regard to the timing of step onset could be accounted for by some major methodological differences. First, the perturbations used by Luchies et al. were predictable in direction, and identical perturbations were presented sequentially. In light of evidence that aging can affect adaptive capabilities (19,20), it is possible that some elderly subjects reached their stability limits sooner because they were less able to adapt their responses to take advantage of the predictable features of the testing paradigm. Differences in instructional set may also account for the differences in findings. Although Luchies et al. did not report the instructions given to the subjects, it appears that they may have been encouraged to resist stepping. In this situation, the elderly may step earlier than the young because they are less prepared to risk losing balance.

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### Table 1. Response Frequency and Characteristics of the Initial Step for the Four Different Classes of Stepping Responses

<table>
<thead>
<tr>
<th></th>
<th>Single Step</th>
<th>Same Leg</th>
<th>Alternate Legs — Same Direction</th>
<th>Alternate Legs — Opposite Direction</th>
</tr>
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<tbody>
<tr>
<td><strong>FORWARD translation — backward 1st step</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>33</td>
<td>11</td>
<td>22</td>
<td>2</td>
</tr>
<tr>
<td>Freq (%) Young</td>
<td>80</td>
<td>4</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>Elderly</td>
<td>30</td>
<td>23</td>
<td>42</td>
<td>3</td>
</tr>
<tr>
<td>AP step (cm)</td>
<td>–26 (1.5)</td>
<td>–33 (2.6)</td>
<td>–14 (1.7)</td>
<td>–31 (1.2)</td>
</tr>
<tr>
<td>ML step (cm)</td>
<td>2.2 (0.8)</td>
<td>0.3 (1.0)</td>
<td>1.5 (0.5)</td>
<td>–1.3 (1.3)</td>
</tr>
<tr>
<td>Onset of asymmetry (msec)</td>
<td>197 (8)</td>
<td>235 (12)</td>
<td>213 (10)</td>
<td>225 (15)</td>
</tr>
<tr>
<td>Onset of unloading (msec)</td>
<td>268 (13)</td>
<td>248 (11)</td>
<td>236 (9)</td>
<td>245 (10)</td>
</tr>
<tr>
<td>Swing (msec)</td>
<td>124 (8)</td>
<td>159 (24)</td>
<td>112 (7)</td>
<td>195 (70)</td>
</tr>
<tr>
<td>Foot-off (msec)</td>
<td>404 (15)</td>
<td>367 (12)</td>
<td>345 (10)</td>
<td>347 (17)</td>
</tr>
<tr>
<td>Foot-contact (msec)</td>
<td>529 (18)</td>
<td>527 (18)</td>
<td>458 (10)</td>
<td>542 (52)</td>
</tr>
<tr>
<td>AP COM (cm)</td>
<td>–9.8 (0.3)</td>
<td>–9.6 (0.6)</td>
<td>–9.3 (0.6)</td>
<td>–8.9 (1.6)</td>
</tr>
<tr>
<td>AP COM velocity (cm/s)</td>
<td>–24 (2)</td>
<td>–33 (1)</td>
<td>–37 (3)</td>
<td>–33 (1)</td>
</tr>
<tr>
<td>ML COM (cm)</td>
<td>0.8 (0.2)</td>
<td>0.7 (0.2)</td>
<td>0.9 (0.6)</td>
<td>0.7 (0.2)</td>
</tr>
<tr>
<td>ML COM velocity (cm/s)</td>
<td>11 (1.3)</td>
<td>9 (2)</td>
<td>11 (1)</td>
<td>7 (2)</td>
</tr>
<tr>
<td><strong>BACKWARD translation — forward 1st step</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>23</td>
<td>21</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Freq (%) Young</td>
<td>48</td>
<td>13</td>
<td>22</td>
<td>17</td>
</tr>
<tr>
<td>Elderly</td>
<td>29</td>
<td>44</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>AP step (cm)</td>
<td>31 (1.3)</td>
<td>32 (1.3)</td>
<td>18 (2.0)</td>
<td>29 (2.4)</td>
</tr>
<tr>
<td>ML step (cm)</td>
<td>3.9 (1.0)</td>
<td>3.1 (0.7)</td>
<td>3.0 (1.3)</td>
<td>5.1 (1.7)</td>
</tr>
<tr>
<td>Onset of asymmetry (msec)</td>
<td>263 (13)</td>
<td>237 (16)</td>
<td>242 (15)</td>
<td>203 (12)</td>
</tr>
<tr>
<td>Onset of unloading (msec)</td>
<td>334 (12)</td>
<td>284 (13)</td>
<td>291 (23)</td>
<td>250 (14)</td>
</tr>
<tr>
<td>Swing (msec)</td>
<td>148 (13)</td>
<td>127 (12)</td>
<td>89 (12)</td>
<td>136 (14)</td>
</tr>
<tr>
<td>Foot-off (msec)</td>
<td>465 (13)</td>
<td>412 (15)</td>
<td>394 (10)</td>
<td>370 (20)</td>
</tr>
<tr>
<td>Foot-contact (msec)</td>
<td>613 (21)</td>
<td>539 (20)</td>
<td>483 (10)</td>
<td>506 (23)</td>
</tr>
<tr>
<td>AP COM (cm)</td>
<td>15 (0.6)</td>
<td>14 (0.4)</td>
<td>18 (3.7)</td>
<td>13 (0.6)</td>
</tr>
<tr>
<td>AP COM velocity (cm/s)</td>
<td>20 (3)</td>
<td>29 (2)</td>
<td>49 (9)</td>
<td>32 (4)</td>
</tr>
<tr>
<td>ML COM (cm)</td>
<td>1.5 (0.3)</td>
<td>1.7 (0.2)</td>
<td>1.6 (0.5)</td>
<td>2.1 (0.4)</td>
</tr>
<tr>
<td>ML COM velocity (cm/s)</td>
<td>14 (2)</td>
<td>13 (1)</td>
<td>11 (2)</td>
<td>18 (2)</td>
</tr>
</tbody>
</table>

**Notes:** Data are shown separately for responses evoked by forward and backward platform translations. Frequencies are based on a total of 25 trials in each direction for the young subjects and 45 responses in each direction for the elderly subjects. Mean and standard errors are provided for continuous data. Measures of COM displacement and velocity were made at the time of foot-contact. Positive ML values indicate motion toward the swing-leg side.
in behavior following the initial foot-contact. These were highlighted by distinct age-related differences in the frequency of multiple stepping and the characteristics of the later steps. Luchies et al. (3), who also reported increased multiple stepping in the elderly, have suggested that multiple stepping, using small and quick steps, may represent a "conservative" strategy in that it allows more opportunities to correct for instability. It is possible that this explanation applies to the "alternate leg/same direction" response that we observed, most prevalently, in the backward step responses of the elderly subjects, and it is therefore significant that Luchies et al. (3) based their hypothesis on observations of backward stepping. However, the majority of the stepping reactions, in young and elderly, featured large initial steps, particularly when stepping in the forward direction. Moreover, in the present study, it would appear that many of the multiple-step responses emerged as a consequence of events that arose after the initiation of the first step, rather than as a strategy planned in advance. This is most clearly supported by the presence of lateral steps directed toward the swing-leg side. The second laterally directed step would only be necessary if there were lateral instability resulting from the execution of the compensatory reactions. In over 30% of the stepping reactions in the elderly, there was a lateral component to the later steps, which was rarely evident in the young subjects. This lateral stepping may reflect an impaired ability to control a lateral instability that arises after the initial foot-contact. Interestingly, there is recent evidence that an impaired ability to control lateral stability may distinguish elderly fallers from nonfallers (23).

Why was the prevalence of multiple stepping in the elderly so high? There was little evidence that the need to execute additional steps resulted from age-related differences in the initial stepping response, i.e., up to the point of foot-contact. This would appear to indicate that the subsequent stepping arose because of events occurring after the initial foot-contact. For example, it is possible that the supporting reactions that should accompany the onset of foot-contact were delayed or inadequate in the elderly. Possibly, this reflects the challenge of detecting and reacting to the need for stabilizing reactions during the course of ongoing movement, and could be due, in part, to an impaired ability to attend to relevant cues (24), amidst the wide array of incoming sensory information associated with the movement in progress. Alternatively, the age-related increase in multiple-step responses might arise because the changes in stability arising during the initial step, although similar in both age groups, are more likely to evoke compensatory stepping behavior in the elderly. For example, it is possible that the later steps were initiated "unnecessarily," due to errors in interpreting the sensory array. A narrower tolerance for instability could have the same effect. This latter point is significant given the fact that, in nearly every trial featuring a forward or backward compensatory step, the COM was moving laterally toward the swing-limb side at time of foot-contact. This lateral excursion could represent a greater perceived challenge for the elderly and hence might be more likely to result in a laterally directed second step. Other possible explanations for the increase in multiple stepping in the elderly include the potentially destabilizing effect of the platform deceleration. It is possible that the ability of the young subjects to anticipate platform deceleration (25) helped them to avoid multiple stepping in later trials; however, Luchies et al. (3) reported remarkably similar age-related differences in the frequency of multiple stepping even though they used an entirely different method of perturbation (a single force impulse applied at the waist).

In summary, the present study provides new insight into the influence of aging on the control of compensatory stepping. The seniors who were tested were healthy, active, and mobile, yet their compensatory stepping reactions were clearly distinct from those of healthy young adults, in terms of the frequency and pattern of their multiple-step responses. In many trials, the resulting instability required very large second or third steps, often in the lateral direction, or even grasping of handrails. The age-related differences in the later steps emerged despite remarkable similarity in many characteristics of the initial step. The impact on stability of both the imposed perturbation and the act of executing the compensatory steps highlighted very real limitations in balance control that might not have been identified using the more traditional tests that assess ability to maintain balance over a fixed BOS. Given the functional significance of BOS changes as a strategy for preserving stability and the age-related differences presently revealed, we believe that an assessment of the capacity to preserve stability against unpredictable perturbation, and specific measures such as the occurrence or placement of multiple steps, may prove to be a significant predictor of falling risk and an important outcome in evaluating or developing intervention strategies to prevent falls.

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