A ge-R elated D ifferences in L aterally D irected C ompensatory S tepping B ehavior

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Background. Lateral falls are common in older adults and are associated with an elevated risk of hip fracture, compared with falls in other directions. Although rapid stepping movements can play an important functional role in maintaining balance, control of lateral stepping is a complex and demanding motor task. This study examined whether there are age-related differences in the stepping behavior used to recover from lateral loss of balance.

Methods. Rapid stepping reactions were evoked in healthy, active young (aged 20–30 years; N = 10) and older (aged 65–73 years; N = 10) volunteers by means of a sudden unpredictable motion of a platform on which the subject either stood quietly or walked in place. Subjects were instructed to respond naturally. Video analysis was performed to characterize the patterns of limb movement evoked by lateral platform motion.

Results. In responding to lateral perturbation of stance, the older adults were much more likely than the young adults to take multiple steps or use arm reactions to regain equilibrium, particularly when attempting crossover steps. During walk-in-place trials, both young and older subjects more frequently used a sequence of side steps rather than crossovers; however, older adults were still more likely to take extra steps or use arm reactions. Collisions between swing foot and stance limb occurred in 55% of walk-in-place trials in older adults versus only 8% in young adults.

Conclusions. Control of lateral-stepping reactions appears to create difficulties for active and healthy older adults above and beyond previously reported problems in controlling forward and backward stepping. Impaired control of lateral-stepping reactions may be an early indicator of increased risk for lateral falls and hip fracture and should be an important consideration in the development of clinical approaches to predicting and preventing falls and related injuries.

There is little doubt that difficulty in controlling balance is a major contributor to an increased risk of experiencing falls and sustaining fall-related injuries in older adults. The majority of studies have focused on control of balance in the anteroposterior (a-p) direction or have examined global measures that do not distinguish between the a-p and the lateral components of balance (1); however, there is growing evidence that age- or pathology-related impairments are often more pronounced in the lateral direction (2,3) and that measures of lateral instability may be better predictors of falling risk (4,5). The importance of lateral instability is magnified further when one considers that a sizable proportion of falls involve falling to the side (1,6) and that it is these falls that are most likely to result in debilitating hip-fracture injuries (7–9). Studies of risk factors for hip fracture have suggested that ability to avoid lateral falls may be equally, if not more, important compared with factors such as bone quality or body-mass index (7–9).

To maintain postural stability, the displacement and the velocity of the body’s center of mass (COM) must be regulated with respect to the base of support (BOS) defined by the feet (10–12). Most studies of aging and balance have evaluated tasks requiring the control of the COM over a stationary BOS, i.e., standing with feet kept in place (1); however, the challenges to balance during daily life are often likely to demand rapid changes in the BOS to control stability, i.e., stepping. In fact, compensatory stepping appears to be a prevalent strategy to preserve stability even when the perturbation is relatively small (12–15), yet the control of these reactions is complex and may well challenge the capabilities of older adults. Successful balance recovery, by means of stepping, requires rapid and accurate control of the foot movement as well as the ongoing COM motion in such a way as to arrest the COM within the boundaries of the new BOS established by the step (11,12).

During lateral-step reactions, the foot-movement control is further complicated by the fact that the leg that is most readily unloaded and lifted (because of the lateral COM motion imposed by the perturbation) is subject to restrictions on lateral movement (because of the position of the other leg). The predominant pattern of response observed in a previous study of young adults involved crossing over with the leg that was unloaded by the imposed COM motion (16). This required a long and relatively complex swing trajectory and a prolonged duration of single-leg support in order for the subject to move the foot across the body while circumventing the stance leg. An alternative pattern of response, which involved coordinating a sequence of two side steps (Figure 1A), shortened the swing trajectory and reduced the duration of single-leg support. There exists, in both patterns of response, the potential for collision between the swing foot and the stance limb.

Although age-related changes in a-p stepping behavior have been studied (17,18) and age-related slowing of lat-
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A. stepping responses which extend BOS under falling COM

B. other stepping responses

directional stepping reactions has been noted (19), there has been little or no characterization of age-related differences in lateral stepping behavior in terms of pattern of foot movement and occurrence of overt errors in foot-movement control (i.e., collisions between the swing foot and the stance limb). Indirect evidence that older adults may experience problems in executing effective laterally directed stepping reactions comes from a video study of naturally occurring falls within a geriatric institution: 25% of the 25 falls that were recorded were preceded by unsuccessful attempts by the subject to recover balance by stepping laterally (1,6,15). Moreover, collisions between the swing foot and the stance limb. To deter predictive strategies that would not be possible in responding to the unpredictable events of daily life, the perturbations were designed to be highly unpredictable. As in a-p stepping (17,18), we hypothesized that older adults would be more likely to step to recover balance than young adults and would also be more likely to take additional steps and to move the upper limbs. We further hypothesized that older adults would tend to avoid the demands associated with the crossover response by using instead a sequence of side steps, but would still experience more frequent errors in executing the required foot movements, as reflected by collisions between the swing foot and the stance limb.

METHODS

Subjects

The study involved 10 young adults (aged 20–30 years, average age 24; 5 males; average weight 66 kg, average height 167 cm) and 10 older adults (aged 65–73 years, average age 69; 5 males; average weight 71 kg, average height 163 cm). Inclusion criteria were (i) right-side dominance, (ii) ability to stand 1 minute and walk 10 m without assistance, (iii) ability to understand English instructions, (iv) independent living. Volunteers were excluded if they reported (i) diabetes, (ii) neurological or sensory disorders, (iii) recurrent dizziness or unsteadiness, (iv) use of medications that may affect balance, (v) joint replacement or fusion, (vi) medical conditions that interfere significantly with daily activities, or (vii) functional limitations on use of the limbs. Each subject provided written informed consent to comply with ethics approval granted by the institutional review board. None of the subjects had participated in any previous balance studies.

The subjects all appeared to be physically active and healthy. All reported that they engaged in 30 minutes or more of strenuous ("heart beats rapidly") or moderately strenuous physical activity each week. Self-ratings of general health [Medical Outcomes Study (MOS) 36-item short-form health survey (20)] were high: All young subjects had perfect scores of 100% for "physical functioning"; the older subjects ranged from 60% to 100%, with a mean score of 87%. All older subjects, when assessed with the Activities-Specific Balance Confidence questionnaire (21), demonstrated a high level of self-efficacy related to postural balance [all scored 83% or better, mean score 96%; scores above 80% are generally associated with a high level of function and activity (22)].

Protocol

Postural reactions were evoked by sudden horizontal translation of a computer-controlled movable platform (16) on which the subject either stood or walked in place. The large size of the platform surface (2 m × 2 m) allowed sufficient space for subjects to take two or more steps in any direction. Safety handrails were mounted around the perimeter of the platform. In addition, subjects wore a safety harness that was designed to prevent impact with the floor without otherwise restricting movement or providing proprioceptive feedback that could aid in control of balance. The perturbations were applied unpredictably in terms of time of onset,
direction, magnitude, and/or waveform to deter predictive responses (see Figure 2 for details).

The protocol, detailed in Table 1, comprised 20 stance trials (10 lateral perturbations) and 9 walk-in-place trials (4 lateral perturbations). In stance trials, subjects stood in a standard position [14° angle between medial foot margins, heel–center spacing = 11% of body height (23)]. For walk-in-place trials, subjects were instructed to step to the beat of a metronome (100 steps/minute, step height 2–3 cm) while keeping the feet within a rectangular boundary circumscribing the standard foot position described above; the perturbation was computer triggered to occur at the onset of a randomly selected step (see Figure 2B). In all trials, subjects held a lightweight rod behind the back in order to deter arm movement; holding this rod was found, in a previous study of young adults, to have no measurable effect on stepping (16). Subjects were instructed to look straight ahead at a visual target (1 m away, at eye level), to try not to move their arms, and to otherwise "do whatever comes naturally to prevent yourself from falling."

Measurements and Analysis

Video recordings from four high-resolution cameras were used to characterize the pattern of limb movement evoked by lateral perturbation, with a grid marked on the platform to determine the placement of the foot. Stepping responses were classified according to the pattern of initial foot movement and placement. As documented in previous studies (15,16), three of these patterns provide overt lateral stabilization by extending the width of the BOS under the falling COM (Figure 1A): (i) the crossover step (COS), in which the swing foot crosses in front of, or behind, the stance foot; (ii) the side-step sequence (SSS), in which an initial small medial step is followed by a second laterally directed step with the contralateral leg; and (iii) the loaded-leg step (LLS), which involves a lateral step with the leg that is loaded by the perturbation-induced COM motion. The other two forms of stepping response do not extend the basewidth in the direction of the initial fall (Figure 1B): (i) the counter-lateral step (CLS), which extends the BOS width in the opposite direction, and (ii) the basewidth-neutral step (BNS), which does not increase the BOS width in either direction.

In addition to classifying the pattern of stepping, we noted any overt problems in moving the swing foot around the stance leg, i.e., observable collisions (contact) between the swing foot and stance limb. To qualify as a collision, there had to be an observable alteration in the trajectory of the swing foot subsequent to the contact (e.g., Figure 3). We also noted any extra limb reactions (additional steps or arm movements of sufficient magnitude to involve releasing the rod) subsequent to the initial stepping reaction. For SSS reactions, the first two steps were considered to comprise the initial reaction because the initial medially directed step (which provides little stabilization in itself) appears to be a preparation for executing a laterally directed step with the contralateral leg (16).

Statistical analyses were performed to test a priori hypotheses that the older subjects, in responding to lateral perturbation, would exhibit increased frequency of stepping, extra steps, and arm reactions (moving the arms or grasping the safety handrails) compared with the young subjects. We also tested the hypothesis that older adults would exhibit an increase in the relative frequency of SSS versus COS responses. Finally, we tested the hypothesis that the older subjects would experience more collisions between the swing foot and the stance limb. We tested each hypothesis by determining the frequency scores (i.e., percentage of trials or percentage of responses) for the individual subjects and then by using the Wilcoxon two-sample (ranked sum) test to analyze the between-group difference in these frequency scores. The criterion level for statistical significance was set to 0.01 ( α = 0.05, with Bonferroni correction for multiple comparisons).

Results

Responses to Lateral Perturbation: Bipedal-Stance Trials

The older and the younger subjects exhibited distinct differences in their postural behavior during lateral stance-perturbation trials. Although there was not a large difference in the frequency of stepping (79/100 trials in older adults versus 62/100 in the young adults; p = 0.58), the stepping responses of the older subjects more frequently involved mul-
Multiple steps (Figure 4) and were twice as likely to involve extra steps (i.e., beyond the initial one-step reaction or two-step sequence): 39% (31/79) of stepping reactions versus 19% (12/62) for the young subjects ($p = .012$). Furthermore, whereas the young adults held the rod behind their back in all 100 trials, the older adults released the rod and moved their arms in 20 of 100 trials ($p = .005$) and actually grasped the safety handrails in 6 of these trials. The above trends were quite consistent across subjects: 7 of 10 older subjects executed extra limb movements in three or more trials whereas none of the young adults executed extra reactions this frequently (Table 2). The trends also remained consistent over time: The frequency of extra limb movements remained high during both halves of the trial block in the older adults [48% (19/40) of stepping trials in first half, 51% (20/39) in second half] and was always much lower in the younger subjects [25% (8/32) in first half, 13% (4/30) in second half].

In 45% (63/141) of all stepping reactions evoked by lateral perturbation of stance, the foot movement provided lateral stabilization by extending the BOS width beneath the falling COM. This was accomplished by COS and SSS responses in 38% (24/63) and 56% (35/63) of these trials, respectively. The third stabilizing pattern, the LLS, occurred in only four trials. The data did not support the hypothesis that the older adults would tend to use the SSS, in preference to the COS, to a greater extent than the young. Although, on average, older adults used the COS response in only 31% (13/42) of COS/SSS reactions versus 65% (11/17) for the young (Figure 5A), this trend was not statistically significant ($p = .40$) nor was it consistent across subjects (only five older adults used the SSS at all and only four younger subjects used the COS; Table 2). It is noteworthy, however, that the older adults almost invariably executed additional steps or grasping reactions in those trials in which they used a COS response (92% or 12/13 cases); in comparison, these extra reactions occurred in only 45% (5/11) of the COS responses in the young subjects (Figure 5B). Additional step or grasp reactions were less frequent when subjects were using a SSS response, in both age groups: Older and young adults executed such additional reactions in 21% (6/29) and 33% (2/6) of SSS responses, respectively.

Collisions between the swing foot and the stance limb occurred only infrequently during the stance-perturbation tri-
terns of stepping was altered dramatically compared with limb movements this frequently (Table 3). More trials whereas none of the young adults executed extra reactions in 2 or steps or arm movements was quite consistent across subjects: 8 of 10 older subjects executed extra reactions in 2 or 36% (135/360) of all trials, whereas the distinct differences, related to the pattern of stepping, in the young and the older subjects. For SSS responses, older subjects were much more likely than the young to execute an extra step or a grasping reaction: 72% (21/29) of SSS responses versus 0% (0/27) in the young. A similar but much less pronounced trend was seen in the COS responses: Older subjects took an extra step versus 18% (6/33) in the younger subjects (p = .32; Figure 5). Nonetheless, there were distinct differences, related to the pattern of stepping, in the young and the older subjects; Figure 4). There was no evidence of an age-related difference in the relative frequency of COS and SSS responses: In older adults, the COS response occurred in 24% (9/38) of trials involving these two patterns of response versus 18% (6/33) in the younger subjects (p = .32; Figure 5). Nonetheless, there were distinct differences, related to the pattern of stepping, in the young and the older subjects. For SSS responses, older subjects were much more likely than the young to execute an extra step or a grasping reaction: 72% (21/29) of SSS responses versus 0% (0/27) in the young. A similar but much less pronounced trend was seen in the COS responses: Older subjects took an extra step or grasped the handrails in 89% (8/9) of COS responses versus 50% (3/6) in the young subjects.

Collisions between the swing foot and stance limb were surprisingly common, occurring in 31% (25/80) of walk-in-place trials, compared with 3% (6/200) in stance-perturbation trials, occurring in 70% (56/80) of all trials, whereas the COS occurred in only 19% (15/80) of trials, and LLS responses did not occur at all. There was no evidence of an age-related difference in the relative frequency of COS and SSS responses: In older adults, the COS response occurred in 24% (9/38) of trials involving these two patterns of response versus 18% (6/33) in the younger subjects (p = .32; Figure 5). Nonetheless, there were distinct differences, related to the pattern of stepping, in the young and the older subjects. For SSS responses, older subjects were much more likely than the young to execute an extra step or a grasping reaction: 72% (21/29) of SSS responses versus 0% (0/27) in the young. A similar but much less pronounced trend was seen in the COS responses: Older subjects took an extra step or grasped the handrails in 89% (8/9) of COS responses versus 50% (3/6) in the young subjects.
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RATION TRIALS (Figure 6). These collisions were much more likely to occur in the older adults: 55% (22/40) of trials versus 8% (3/40) in the young ($p = .002$). The occurrence of a collision was associated with an increased likelihood that the initial reaction would be followed by an additional step or grasping reaction. Such additional reactions occurred in 64% (16/25) of stepping trials that involved collisions, but in only 31% (16/51) of stepping trials that did not involve a collision.

DISCUSSION

The results demonstrated distinct age-related differences in the stepping behavior evoked by unpredictable lateral perturbation. The older adults consistently took more steps than the young to recover equilibrium, they showed a much greater tendency to move the arms and to grasp safety handrails, and they were much more likely to sustain collisions between the swing foot and the stance limb.

Why were the older adults so much more likely than the young to use extra steps or arm movements to recover equilibrium? It is quite possible that the tendency to use additional limb-movement reactions, subsequent to the initial stepping reaction, reflects instability, i.e., the new BOS established by the initial stepping reaction was insufficient to capture and arrest the motion of the COM. A biomechanical model of a-p stepping has, in fact, demonstrated an association between the level of instability of the initial step and the tendency to take additional steps (11). Reduction in the stability of the initial step and a consequent need to execute additional steps or arm reactions could be a result of errors or inadequacies in the planning or execution of the initial step (e.g., because of age-related changes in the neural, sensory, or musculoskeletal systems).

Figure 5. Comparison of crossover-step (COS) and side-step-sequence (SSS) reactions. A. Frequency of COS and SSS reactions, expressed as a percentage of the total number of lateral-perturbation trials (100 stance trials and 40 walk-in-place trials in each age group). Note the high frequency of SSS reactions, in both age groups, during walk-in-place trials. B. Relative frequency of extra stabilizing reactions (i.e., additional steps and/or grasping of handrails) beyond the one step (COS response) or two steps (SSS response) required for executing the initial response. Note that extra reactions were relatively infrequent in both age groups when subjects were executing SSS reactions during stance; however, older adults were much more likely than the young to use extra reactions when executing SSS reactions during walk-in-place trials. Note also the high frequency of extra reactions in the older adults when they were executing COS reactions (both stance and walk-in-place trials).

Figure 6. Frequency of collisions between the swing foot and stance limb. A. The numbers of trials involving collisions are shown separately for COS and SSS reactions, as well as other patterns of stepping (in these latter cases, it appeared that attempts to execute a COS or SSS reaction were abandoned as a result of the collision; the possibility that the collision, in blocking the intended foot movement, caused an intended COS response to become a SSS should also be noted). B indicates the location of contact: FF = swing forefoot against stance forefoot, FR = swing forefoot against stance rearfoot, etc; “medial” indicates that the swing-foot movement was almost purely medial (forefoot contacted forefoot and rearfoot contacted rearfoot).
It is also possible, however, that the tendency to execute additional steps or arm reactions reflects changes in perception of instability or psychological factors, such as fear of falling, rather than an actual decrease in the stability level of the initial step. A third possibility is that unsteadiness or falling, rather than an actual decrease in the stability level of the swing foot could seriously jeopardize stability, and the fact that the collisions were associated with an increased frequency of extra stabilizing reactions appears to support this view. The walk-in-place task was particularly useful in revealing the difficulties in controlling the limb trajectory. This approach shows promise as a practicable method for simulating the challenge of coordinating postural reactions with ongoing movement while avoiding many of the methodological difficulties associated with gait-perturbation studies.

Regardless of the cause of the tendency for a subject to take additional steps or grasp handrails, it is important to consider the consequences of such alterations in behavior. There is, in fact, reason to believe that executing additional reactions could actually jeopardize stability and increase the risk of falling. Each lifting of the foot leads to a lateral instability that must be corrected (18, 24), and each attempt to move the foot leads to the possibility of incurring errors that might further reduce stability, e.g., collisions between the swing foot and the stance limb. In addition, environmental constraints may lead to difficulties when multiple reactions are required for recovering balance. For example, lack of unobstructed space to step and absence of handholds to grasp may preclude use of multiple reactions; such difficulties have been reported to contribute to causing falls (25).

With regard to the pattern of stepping, there appeared to be considerable intersubject variability within each age group regarding the relative frequency with which the COS and the SSS patterns of response were used to provide lateral stabilization during stance-perturbation trials. Nonetheless, the finding that older subjects almost invariably followed their COSs with additional stabilizing reactions suggests that they had substantial difficulty in controlling stability on the occasions when they did use the COS. This finding, in conjunction with the much-reduced incidence of extra reactions during SSS responses, is consistent with the view that the COS response is more demanding to control. In the walk-in-place task, both young and older subjects tended to use the SSS much more frequently than they did the COS; however, in contrast to the young subjects, the older subjects required extra reactions in a high proportion of these responses, and collisions occurred frequently, suggesting that preferential use of the SSS strategy was not entirely successful in avoiding control problems. Note, however, that the high frequency of collisions during these trials may confound interpretation regarding strategy selection, i.e., the collision may have forced the subject to alter the intended response from a COS to a SSS in some trials.

In conclusion, the results of this study suggest that the demands of controlling lateral stepping reactions may create difficulties for active and healthy older adults above and beyond previously reported problems in controlling forward and backward stepping. A novel walk-in-place paradigm was found to be particularly useful in revealing problems in controlling the limb trajectory. Further work is needed to determine the specific neural and biomechanical factors that subjects provide strong evidence of age-related impairment in the control of the reactions. The problem of limb collisions has not been studied previously. It seems likely that the resulting failure or delay in finding an appropriate landing site for the swing foot could seriously jeopardize stability, and the fact that the collisions were associated with an increased frequency of extra stabilizing reactions appears to support this view. The walk-in-place task was particularly useful in revealing the difficulties in controlling the limb trajectory. This approach shows promise as a practicable method for simulating the challenge of coordinating postural reactions with ongoing movement while avoiding many of the methodological difficulties associated with gait-perturbation studies.
contribute to the observed alterations in stepping behavior. From a clinical perspective, impaired control of lateral stepping reactions may be an early preclinical indicator of increased risk for lateral falls and hip fracture and should be an important consideration in the development of clinical approaches to predicting and preventing falls and related injuries. The pronounced age-related differences currently observed suggest that even active, healthy, and relatively young seniors may be at risk. We are currently conducting a prospective study to examine directly whether lateral stepping performance is, in fact, predictive of falling risk in such a population. Further work is needed to study lateral stepping in older and more frail individuals who are likely to exhibit even more profound difficulties in controlling these important postural reactions.

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References


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