Age-dependent differences in lateral balance recovery through protective stepping

Marie-Laure Mille a, Marjorie E. Johnson a, Katherine M. Martinez a, Mark W. Rogers a,b,*

a Department of Physical Therapy and Human Movement Sciences, Feinberg School of Medicine, Northwestern University, Chicago, IL 60611, USA
b Department of Physical Medicine and Rehabilitation, Feinberg School of Medicine, Northwestern University, Chicago, IL 60611, USA

Received 20 August 2004; received in revised form 2 March 2005; accepted 8 March 2005

Abstract

Background. Aging appears to present particular problems for lateral balance stability related to falls. Protective stepping is a common strategy for maintaining balance that may be impaired with aging due to changes in neuromusculoskeletal factors. This study assessed the response patterns, kinematics, and single support hip abduction torque during lateral protective stepping for balance recovery in healthy young and elderly adults.

Methods. Ten healthy elderly and 10 younger adults received stepper-motor driven waist-pulls of bipedal stance applied pseudorandomly to either side. Stepping response strategies were quantified with force platforms and motion analysis.

Findings. The young responded primarily using a single lateral sidestep with the limb that was initially loaded passively by the waist-pull, while older subjects favored crossover stepping using multiple steps with more inter-limb collisions. When the elderly did use loaded side steps, the steps were longer, slower, and higher and included greater and prolonged lateral trunk motion than in the young. Overall, older subjects produced greater and less rapid stabilizing hip abduction torque during the single support phase.

Interpretation. Age-associated differences in lateral balance control through stepping included using a riskier recovery strategy with increased collisions between the limbs, multiple steps, altered first step characteristics and lateral trunk motion during direct sidestepping, and a generally greater support hip torque. The difficulties with lateral balance control in aging may reflect factors such as impaired hip abduction torque-time capacity and lateral trunk mobility/control. Our findings contribute additional knowledge pertaining to the problem of balance dysfunction and falls among the elderly.

© 2005 Elsevier Ltd. All rights reserved.

Keywords: Aging; Falls; Lateral balance; Stepping; Neuromusculoskeletal factors; Rehabilitation

1. Introduction

Maintenance of postural balance while standing is a vital aspect of human movement function. Difficulties in controlling balance increase the risk of falling and fall-related injuries. This is particularly true with advancing age where impairments in neuromusculoskeletal factors generally increase (Guralnik et al., 1995; Nevitt et al., 1989; Studenski et al., 1991; Tinetti et al., 1988) and contribute to balance dysfunction that precipitates falls.

There is accumulating evidence that aging effects on balance may be accentuated in the lateral direction. For example, measures of medio-lateral (M-L) postural sway in older individuals have been associated with both past falls (Lord et al., 1999) and future risk of falls.
As a motor control problem, stepping requires that the central nervous system regulate the spatial and temporal relationship between the position and motion of the center of mass (CoM) in interaction with the changing base of support (BoS). Compared with younger adults, older subjects have been previously observed to direct their initial step (fallers) (Rogers et al., 2001) or subsequent steps (non-fallers) (McIlroy and Maki, 1996) more laterally in response to forward or backward disturbances of standing balance. These findings suggested that the elderly might have difficulty with controlling lateral instability during protective stepping.

In comparison with antero-posterior (A-P) induced stepping, lateral perturbations involve distinctly different biomechanical demands that affect the characteristics of M-L protective stepping. An externally applied lateral disturbance of stationary standing would move the CoM relative to the BoS and thereby redistribute the vertical load supported beneath each leg. The leg opposite to the direction of the impending fall undergoes a relative passive unloading that could facilitate a more rapid swing foot liftoff (Maki et al., 1996). While an unloaded limb step reduces the need to actively redistribute weight bearing from bipedal to single limb support in anticipation of stepping it often involves a more complex and prolonged crossover step trajectory that increases the potential for collisions between the limbs (Maki et al., 2000). Alternatively, a direct sidestep with the passively loaded limb would require additional effort to unload the swing limb and establish a new BoS configuration. Another alternative involves a medial–lateral sidestep sequence of the unloaded and loaded limbs respectively. In all cases, the pattern of lateral stepping used is likely dependent upon hip joint abductor–adductor torque production and regulation of lateral trunk motion (Rietdyk et al., 1999; Rogers and Mille, 2003) that are frequently impaired among older individuals (Johnson et al., 2004; Schenkman et al., 2000; Schenkman et al., 1996).

A previous report described differences with age in the strategy selection and efficiency (number of steps) of lateral stepping reactions (Maki et al., 2000). Further information is needed, however, about the kinematic and kinetic factors contributing to aging deficits in lateral balance recovery through stepping. The aim of this study was to determine age-related differences in protective stepping behavior in response to lateral waist-pull perturbations of postural balance. We hypothesized that older adults would demonstrate age-dependent differences in controlling lateral stepping in conjunction with altered support hip torque-time capacity and lateral motion control of the trunk.

2. Methods

2.1. Subjects

Twenty healthy, community dwelling women signed informed consent to participate in this study that was approved by the Institutional Review Board of Northwestern University. Ten young adults aged from 23 to 27 were recruited from the university student population [mean age: 24 (SD 1.4) years; mean height: 167.3 (SD 5.0) cm; mean weight: 60.9 (SD 6.3) kg]. Ten older adults aged from 64 to 85 were recruited through an Aging Research Registry and Geriatric Evaluation Service [mean age: 73.3 (SD 6.3) years; mean height: 159.3 (SD 5.1) cm; mean weight: 62.7 (SD 14.2) kg]. Exclusion criteria included a history of significant cardiovascular, pulmonary, neurological or musculoskeletal disorders; any history of falls within the past year; a score of 20 or below on the Mini-Mental State Exam (Folstein et al., 1975) and use of medications classified as sedatives, anti-depressants or neuroleptics.

2.2. Methods

Subjects stood in a comfortable standing position with each foot on a separate force platform (Advanced Mechanical Technology Incorporated, Newton, MA, USA). Subjects used a self-selected stance width about 20% of their height with the feet as parallel as possible. The stance width did not differ between the groups (Mann–Whitney test, \( P = 0.315 \)). Foot position was marked on the ground to ensure consistency between trials. Subjects wore a safety harness that prevented them from falling but otherwise did not constrain their movements. Protective stepping responses were evoked by a motor-driven waist-pull system (Pidcoe and Rogers, 1998) that delivered lateral pulls of constant magnitude (amplitude: 22.5 cm; velocity: 31.5 cm s\(^{-1}\) and acceleration: 900 cm s\(^{-2}\)) on either side of the body. Two flexible cables were attached on one end to a rigid connection on a belt at the level of the subject’s waist and on the other
end to the puller system. Subjects received 10 perturbation trials for each side presented in a pseudorandom order that was the same between subjects. They were instructed to “react naturally to prevent themselves from falling” in response to the perturbation. No practice trials were provided such that the potential effects of learning might have influenced their performance during the multiple trials.

Body segment kinematics were recorded for 5 s at a sampling rate of 60 Hz using a six-camera motion analysis system (Motus, Peak Performance Company, Englewood, CO, USA) that captured the motion of reflective markers placed over 17 bony landmarks. Markers were placed bilaterally between the second and third metatarsals, and on the lateral malleolus, the knee joint line posterior to the lateral femoral condyle, greater trochanter, acromion, lateral epicondyle of the elbow, dorsum of the wrist between the styloid processes, ear canal, and on the crown of the head. Ground reaction forces were also recorded for 5 s at a sampling rate of 500 Hz.

2.3. Data analysis

Patterns of response for each trial were characterized by recording the step efficiency (i.e. the number of steps required by the subject to recover their balance), the stepping strategy (i.e. the first step side relative to the perturbation side) and the incidence of collisions between the limbs. For each of these variables, subject’s frequency scores (i.e. percentage of trials) were then calculated. First step characteristics were determined from the kinematic recordings of the step side ankle marker. The onset and end of the step were defined from the vertical velocity of the marker in order to identify the step duration. Step displacements were assessed as the displacement of the ankle marker movement between step onset and end in the A-P and M-L directions, and step clearance was calculated as the maximum vertical displacement. All step displacements were expressed as a percentage of the subject’s height. The trunk angular displacement in the frontal plane was computed as the angle of the median trunk axis (line connecting the mid point between the greater trochanters and the mid point between the shoulders) with the vertical.

The characteristics of the vertical ground reaction forces under the stepping leg were identified by finding the peak of the vertical force, which corresponded with the onset of unloading. The duration of the loading was calculated as the time needed to reach maximum vertical force and the increase in force from baseline was expressed as a percentage of body weight (BW) (Fig. 1). The duration of the unloading phase was defined as

![Fig. 1: Left. Representative time histories of the vertical ground reaction forces (continuous line) under the initial swing leg (black) and the stance leg (gray), and of the vertical ankle displacement of the swing leg (dashed line) during the predominant loaded limb sidestepping strategy of the younger subjects (i.e. the leg initially loaded passively by the waist-pull) in response to a lateral waist-pull perturbation of stance (horizontal arrow). Right. Representative time history of the same data types during the predominant unloaded limb crossover stepping strategy of the older subjects (i.e. the leg initially unloaded passively by the waist-pull). The two dotted vertical lines correspond from left to right to the onset the vertical force changes and the end of unloading (i.e. zero force) under the first swing limb.](image-url)
the time from maximum vertical force through zero vertical force at first step liftoff. 

Markers on the greater trochanter, lateral femoral epicondyle, and lateral malleolus of the stance leg were used to approximate ankle, knee, and hip joint centers of rotation. We assumed a three-link model for estimating the muscular contribution to the net hip joint abduction-adduction torque in the frontal plane similar to approaches used previously (De Looze et al., 1992; Leskinen, 1985; Toussaint et al., 1995). While a three dimensional analysis may be more appropriate for this kind of task, we believe that the isolated planar analysis yields valid and reliable results because Coriolis and gyroscopic influences were minimal. Segments were assumed to be rigid and connected by frictionless pin joints. A planar, Newtonian approach was used to formulate the equations of motion for determining net inter-segmental joint reaction forces and torques using a bottom-up analysis. Forces and moments measured by the force plate were used as the input kinetics on the foot segment, which was the initial link in a dynamic chain of rigid bodies connected by the ankle, knee, and hip. The foot was assumed to be stationary on the ground. The positions of segmental mass centers of gravity, and segmental masses and their moments of inertia were estimated from the anthropometric data of each subject (Winter, 1990).

Since the sampling rates were different between the kinetic and kinematic data, frontal plane shank and thigh angles were resampled at the same frequency as the ground reaction forces using a cubic spline interpolation.

2.4. Statistics

Differences between groups were assessed using the Mann–Whitney U-test for independent samples. For the subjects using more than one stepping strategy, difference between these strategies were tested using the Wilcoxon’s Signed Rank Test for a paired sample. For all comparisons, differences were considered significant at \( P < 0.050 \).

3. Results

3.1. Pattern of responses

All subjects stepped in all trials in response to the perturbations. As expected, the step efficiency was different between the two groups \( (P < 0.001) \). Younger subjects needed only one step to recover their balance in 88% of the trials whereas older adults used multiple steps in 65% of the trials (Table 1).

Table 1
Inter-subject variation in pattern of response to lateral perturbations

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of trials</th>
<th>Number of steps</th>
<th>Stepping strategies</th>
<th>Collision between feet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subjects</td>
<td>Single/Multiple</td>
<td>LSS/UMS/UCS</td>
<td></td>
</tr>
<tr>
<td>Young adults</td>
<td>1</td>
<td>18/2</td>
<td>0/0/20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>19/1</td>
<td>2/0/18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>16/4</td>
<td>18/2/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>20/0</td>
<td>19/0/1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>19/1</td>
<td>0/0/20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>18/2</td>
<td>18/2/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>19/1</td>
<td>20/0/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>16/4</td>
<td>15/4/1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>15/6</td>
<td>17/1/1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15/6</td>
<td>6/3/12</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>175</td>
<td>25</td>
<td>115/12/73</td>
<td></td>
</tr>
<tr>
<td>Older adults</td>
<td>1</td>
<td>1/19</td>
<td>11/3/6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15/5</td>
<td>6/0/14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>13/7</td>
<td>13/4/3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0/20</td>
<td>0/8/12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3/17</td>
<td>5/2/13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0/20</td>
<td>1/0/19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>17/3</td>
<td>0/0/20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>16/2</td>
<td>0/0/18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>5/17</td>
<td>11/0/11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0/20</td>
<td>19/0/1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>70</td>
<td>130</td>
<td>66/17/117</td>
<td></td>
</tr>
</tbody>
</table>

a The total number of perturbation trials was 200 in each age group.

b LSS = Loaded Side Step; UMS = Unloaded Medial Step; UCS = Unloaded Crossover Step.
Two main stepping strategies were observed in response to the lateral perturbation that initially caused a passive increase in load beneath the leg nearest to the destabilization side and a concomitant reduction in load beneath the opposite limb (Fig. 1). The first strategy consisted of performing a side step with the passively loaded leg and is referred to as a Loaded Side Step (Fig. 1, left). Overall, this strategy tended to be used more often by the younger group and was observed in 57.5% of trials; whereas older subjects used this strategy in only 33% of trials. However, no statistical difference was found between the groups in the use of the Loaded Side Step strategy ($P = 0.190$) mainly because two of the younger subjects never used this strategy (Table 1).

The second strategy consisted of performing a crossover step, either in front of or behind the body, with the passively unloaded leg and is referred to as an Unloaded Crossover Step (Fig. 1, right). Overall, the older subjects used this strategy during 58.5% of trials, whereas younger subjects performed unloaded crossover Steps in 36.5% of trials. Again, no statistical difference between the groups was observed in the use of the Unloaded Crossover Step strategy ($P = 0.165$) mainly because three of the older subjects did not use this strategy predominantly (Table 1). Compared with Loaded Side Step trials, Unloaded Crossover Steps included a greater number of collisions between the limbs during the first step (Table 1).

In 7.25% of the trials involving less than half of the subjects, a third strategy was observed (Table 1). In this case, the passively unloaded limb was moved medially towards the other leg without crossing over the stance leg. Such steps are referred to as an Unloaded Medial Step and always involved multiple steps. Because of the low occurrence of this strategy, Unloaded Medial Step trials were omitted from further analyses.

### 3.2. Ground reaction force characteristics

The vertical force ($F_z$) characteristics for each step strategy were generally similar between the groups (Fig. 2). For Loaded Side Step trials, the $F_z$ onset ($P = 0.132$), the loading phase amplitude ($P = 0.643$) and duration ($P = 0.487$), and the unloading phase duration ($P = 0.203$) were similar for the younger and older subjects. The Unloaded Crossover Step unloading phase duration was also similar between the young and old ($P = 0.266$). However, the $F_z$ onset time occurred marginally earlier ($P = 0.06$) in the Unloaded Crossover Step trials for the young. Overall, when the two stepping strategies where compared across the groups, the $F_z$ onset tended to be earlier for the Loaded Side Step strategy than for the Unloaded Crossover Step ($P = 0.06$).

### 3.3. Stepping characteristics

Younger and older subjects were as fast to initiate the first step regardless of the stepping strategy used (Loaded Side Step: $P = 0.25$; Unloaded Crossover Step: $P = 0.33$). However, in the Loaded Side Step strategy, older subjects executed a larger lateral displacement ($P < 0.001$), and a higher ($P < 0.001$) and longer duration ($P < 0.01$) lateral step than the younger subjects (Fig. 3). No differences in the characteristics of the first step were observed between the two groups for the Unloaded Crossover Step strategy. Because the Unloaded Crossover Step strategy required a more complex trajectory of the foot, the first step was larger ($P < 0.002$), longer ($P < 0.002$), and tended to be higher ($P < 0.06$) than in the Loaded Side Step strategy.
3.4. Trunk motion

Following the lateral waist-pull, the initial trunk response (Fig. 4) was always characterized by a counter-rotation away from the direction of the perturbation that occurred prior to and during the first step. This was followed by a reversal in trunk motion direction that reached a peak displacement after the completion of the first step (Fig. 4, left).

When a Loaded Side Step was executed, the initial counter-rotation phase was significantly longer in duration ($P < 0.015$) and tended to be larger in amplitude ($P = 0.072$) in the old compared to the young (Fig. 4, right). No statistical differences between the groups were found in the characteristics of the counter-rotation phase for the Unloaded Crossover Step strategy ($P > 0.310$) (Fig. 4, right).

When comparing the two stepping strategies (Fig. 4, right), a larger amplitude ($P < 0.022$) and a longer duration ($P < 0.028$) of the counter-rotation phase were observed during the Unloaded Crossover Step compared to the Loaded Side Step strategy. Furthermore, the phase reversal time occurred later ($P < 0.038$) relative to the step onset in the Unloaded Crossover Step com-
pared to the Loaded Side Step strategy [353 (SD 166) ms and 148 (SD 94) ms, respectively].

3.5. Hip torque

The single limb stance phase of the step was characterized by a hip abduction torque to stabilize the body in the M-L direction under the action of gravity (Fig. 5). The maximum mean support hip joint torque was 12% higher for the older subjects than for the young ($P < 0.013$). The time to reach this maximum was also longer for the older subjects than for the young ($P < 0.006$). No differences between these two parameters were found for the two types of stepping strategies ($P > 0.308$).

4. Discussion

Overall, the results identified age-dependent differences in lateral balance recovery through protective stepping induced by external perturbations of bipedal stance. Older subjects were less efficient in recovering their balance as indicated by the greater number of steps taken and the tendency to select a more complex and hazardous form of stepping strategy with more inter-limb collisions. The elderly took larger, longer duration, and higher initial lateral sidesteps, and showed altered trunk motion characteristics and a greater support hip abduction torque. These findings provide several new biomechanical insights about aging changes in lateral balance function when steps are executed to recover standing equilibrium.

The use of multiple steps to recover balance has been a consistent finding of prior studies of protective stepping in the elderly regardless of the direction of the imposed disturbance to postural balance (Hsiao and Robinovitch, 2001; Luchies et al., 1994; Maki and McIlroy, 1999; Pai et al., 1998; Rogers et al., 2001). For forward steps, the tendency for older adults to step more often than younger subjects has been well predicted by a reduced margin of stability modeled as the position–velocity relationship between the CoM and BoS (Pai et al., 1998). Other models of A-P stepping also have found an association between the CoM and BoS relationship of the first step and the use of additional steps (Hsiao and Robinovitch, 2001; Maki and McIlroy, 1999).

Similar to past studies that used moving platform perturbations to induce stepping (Maki et al., 2000; Maki et al., 1996), we found three forms of lateral stepping strategy. Subjects either side-stepped with the leg that was initially loaded passively by the waist-pull (Loaded Side Step), or stepped with the leg unloaded passively by crossing over the stance leg (Unloaded Crossover Step) or by executing a side step sequence through a small medial step followed by a longer lateral step with the opposite leg (Unloaded Medial Step).

In contrast to the prior observation that younger and older subjects together used a medial–lateral sidestep sequence in 56% of the trials (Maki et al., 2000), the Unloaded Medial Step strategy was rarely observed in our study. This difference in the percent of appearance of this strategy might, at least in part, reflect the differences in the types of perturbations used to induce stepping. Since a support surface translation applied during bipedal stance directly displaces the ground contact surface away from the BoS it affects the integrity of the foot-floor surface interface where the ground reaction forces are normally exerted. Such effects are minimized during lateral waist-pull perturbations that are applied nearer to the CoM. However in both cases, the initial medial step with the passively unloaded foot, which is often small (e.g. 10–20 cm), might be passive in nature rather than an actively generated step. The second sidestep of the sequence in the direction of the impending fall that is considerably longer in length than the initial medial step, likely represents the stabilizing element of the response by reconfiguring the BoS.
Despite notable inter-subject variability in both groups, we observed that younger subjects primarily reacted to lateral perturbations with a loaded limb side stepping strategy while older subjects tended to more often perform a crossover step with the passively unloaded limb. It is acknowledged that, because of the variability of strategy selection between individuals within each of the groups, larger sample sizes would help to determine the robustness of the findings concerning age-dependent differences in step recovery strategies. Nevertheless, the present results are in contrast with the aforementioned study where both younger and older subjects primarily used the unloaded leg in 94% of the trials and where only four Loaded Side Steps were observed (Maki et al., 2000). It has been proposed that subjects may often select to use a stepping response with the limb that is passively unloaded by the perturbation since the reduced load would allow a faster response by assisting with limb withdrawal and foot swing (Maki et al., 1996). However, we could not confirm this hypothesis during waist-pull induced stepping since the first step onset timing across the groups was the same for loaded limb side steps and unloaded limb crossover steps.

Compared with loaded limb sidestepping, selection of the unloaded limb during crossover stepping might reduce the step initiation timing in some situations. However, this potential advantage is countered by several disadvantages. These include an increased time spent in the unstable single limb support phase, a longer and more complex foot trajectory associated with the increased risk of collision with the stance limb, and a potentially smaller and less stable BoS area at first step foot contact. The fact that we observed a much greater incidence of collisions between the limbs for crossover steps compared with sidestepping suggested that crossing over the stance limb may be a particularly hazardous form of balance recovery particularly for older adults. The predominant use of a single loaded limb sidestep by younger adults to extend the BoS to arrest the motion of the falling CoM, may be more difficult for older subjects to perform due to aging changes in specific neuromusculoskeletal factors. The fact that the change in swing limb vertical loading force for the Loaded Side Step occurred earlier for both groups than for the Unloaded Crossover Step, suggested that a more rapid response is required for the lateral sidestep. This might relate to aging reductions in hip abductor–adductor muscle torque-time capacity (Johnson et al., 2004) that impose limitations on older subjects' ability to complete the series of inter-limb hip controlled tasks needed to unload and advance the loaded limb while maintaining stabilizing support of the single stance limb (Rietdyk et al., 1999; Rogers and Mille, 2003).

In support of the foregoing, the older subjects demonstrated several differences in their Loaded Side Step kinematic characteristics when compared with the young. These alterations included a longer step distance and duration and greater height during lateral sidestepping with the loaded limb that did not occur for crossover steps with the unloaded limb. It was noteworthy that the onset timing of the first step was as fast for the old as for the young during both Loaded Side Step and Unloaded Crossover Step strategies, which is consistent with other studies of induced stepping (Luchies et al., 2002; Rogers et al., 2001). The fact that the first step characteristics across the groups were higher and longer in distance and duration for the Unloaded Crossover Steps than for the Loaded Side Steps, reflected their more complex trajectory requirements (Maki et al., 2000; Maki et al., 1996).

To our knowledge, trunk motion characteristics in the frontal plane during protective stepping have not been reported previously. In all cases, an initial lateral rotation of the trunk segment occurred prior to and during the first step in the direction opposite to that of the waist-pull so as to counteract the impending instability. This counter-rotation phase was followed by a reversal in trunk motion in the opposite direction during the first step. In Loaded Side Step trials, the counter-rotation phase was prolonged and larger in amplitude for the old compared with the young suggesting that the motion of the trunk was either less well regulated or intentionally exaggerated in response to the perturbation. Differences in trunk movements between the groups were not observed for Unloaded Crossover Step trials. This again suggested particular differences with age in performing lateral sidestepping with the initially loaded limb. In both groups, the larger amplitude and longer duration of the counter-rotation phase and delay in starting the reversal phase for Unloaded Crossover Step compared with Loaded Side Step, presented additional challenges to maintaining lateral stability when a crossover strategy is used. For example, the increased motion of the trunk and timing changes would likely contribute to further destabilizing postural balance since the momentum of the trunk was still directed towards the unsupported side after the leg was withdrawn from the ground. This might have represented a further impediment to sustaining lateral balance among those elderly who more often used crossover stepping since limitations in trunk mobility are a frequent companion of older age (Schenkman et al., 1996).

The generation of hip abduction torque is an important contributor to the regulation of M-L stability during the single limb stance phase of stepping as well as for ongoing gait (MacKinnon and Winter, 1993). For Loaded Side Step and Unloaded Crossover Step reactions combined, the older subjects produced a peak hip abduction torque during the single limb stance phase of the first step that was 12% greater than the abduction torque of the younger subjects. This was accompanied by a longer time to reach peak torque for the old than for the young.
Because reductions in maximum hip abduction torque-time production as large as 40% have been identified for even healthy, community living older women (Johnson et al., 2004), it was not unexpected to observe age-associated differences in stabilizing hip torque between the groups. Thus, to achieve a torque level that was functionally adequate to provide M-L stability during single limb support, the older subjects likely generated greater neuromuscular effort relative to their maximum capacity than younger subjects. A reduced torque generating capacity of older adults has been previously associated with a greater relative effort (i.e., the percentage of joint moment relative to maximal joint moment) during stair climbing and chair rise activities (Hortobagyi et al., 2003). This implied that the older adults’ difficulty with performing mobility activities of daily living might be related to a reduction in their neuromuscular reserve capacity. The slower rate of torque production could also have disadvantaged the older subjects in such time-critical balance recovery situations. Our currently ongoing studies are examining further the extent to which age-related differences in lateral balance recovery are attributable to impairments in hip abductor–adductor torque-time capability and in mobility/control of lateral trunk motion during protective stepping and other balance functions (Rogers and Mille, 2003). Identification of neuromusculoskeletal impairments affecting postural balance in older adults would provide mechanistic bases for targeted interventions aimed at improving balance function and reducing the risk of falls and related disabilities.

5. Conclusions

We have demonstrated several age-related differences in protective stepping responses for the recovery of lateral postural balance following waist-pull disturbances of stationary standing. Healthy younger and older adults used two primary stepping strategies that consisted of either a lateral side step with the limb that was initially loaded by the waist-pull, or a crossover step with the passively unloaded limb. Overall, sidestepping tended to be more common for the young while the old showed a tendency to more often perform crossover stepping. Balance recovery was less efficient for the elderly subjects who more frequently used multiple steps compared with the young who mostly needed a single step to regain stability. In addition to a greater incidence of collisions between the limbs, older subjects showed several differences in their first step characteristics that indicated particular difficulties with performing lateral sidestepping with the passively loaded limb. Compared with younger adults, these stepping responses for older subjects were accompanied by alterations in lateral trunk motion characteristics and support hip abduction torque-time production. Impairments in these neuromusculoskeletal factors could be at the source of the particular problems with lateral stability and balance dysfunction encountered by many older individuals. Further insight awaits determination of the passive and active motion contributions.

Acknowledgement

The contributions of T. Brown, B. Edwards, L. Hedman, S. Kermath, A. Muller, L. Stalling, and J. Zhang to this project are gratefully acknowledged. This work was supported by NIH grant AG16780.

References