

Lateral Stability and Falls in Older People

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ROGERS, M. W., and M.-L. MILLE. Lateral stability and falls in older people. *Exerc. Sport Sci. Rev.*, Vol. 31, No. 4, pp. 182–187, 2003. Aging changes in specific neuromusculoskeletal factors affecting protective stepping and other balance functions may precipitate lateral instability and falls. Identification of these factors provides directives for novel therapeutic interventions to reduce fall risk in older people. **Keywords:** age, standing equilibrium, step reactions, frontal plane, imbalance, motor control, physical rehabilitation

INTRODUCTION

An increased susceptibility to falling leading to functional disability is one of the major problems associated with human aging. Even in the absence of injury resulting from falling, a tendency to lose balance among the elderly often results in an overall reduction in the level of physical activity and to a decreased ability to function satisfactorily in social roles.

From a balance control perspective, the safe and effective performance of everyday functional activities while standing is critically dependent on an individual's ability adequately to regulate the relationship between the body center of mass (COM) and the base of support (BOS), usually represented by the feet. Standing stability refers to the maintenance of the relative position and motion of the COM with respect to the BOS. Lateral instability, or loss of balance in the frontal plane, occurs when the motion characteristics of the COM with respect to the BOS exceed certain spatiotemporal stability limits. Most past studies of balance control with aging traditionally have focused on the postural strategies used to maintain the COM over an unchanging feet-in-place BOS. More recently, however, it has become increasingly apparent that active movements of the limbs such as stepping, which modify the BOS, are a more commonly executed control strategy for protection against falling in the natural environment (6,8,10). It is also evident that many older individuals,

particularly those who experience falls, have an increased reliance on stepping, rather than feet-in-place response strategies, to maintain balance (6,8,10).

There are several indications that age-associated impairments of lateral stability may be a particularly important aspect of balance dysfunction leading to falls and sustaining fall-related injuries. The question that arises is why do many older people appear to be particularly vulnerable to lateral instability of postural balance in association with an increased risk for falling and fall related injuries? We hypothesize that changes in specific neuromusculoskeletal factors with age compromise important lateral stabilization and balance functions and increase the risk of falls among many older people. The purpose of this brief review is to examine the evidence in support of this hypothesis. Because of its importance to maintaining balance in daily life, this review focuses on information derived from studies of the control of protective stepping function.

BALANCE DYSFUNCTION, LATERAL STABILITY, AND FALLS

An impaired ability to control postural balance stability in the lateral plane of motion appears to be particularly relevant to the problem of falling among older people (see (5,8) for reviews). For example, aging effects on balance may be accentuated in the mediolateral (M-L) direction, and measures of M-L sway are well associated with future risk of falls and past falls. Clinical observations indicate that older individuals often are unable to move from two-legged to one-legged support at least in part because of difficulties with controlling lateral motion of the body. Other information suggests that single-leg balance ability may also predict falls. Moreover, falls often involve lateral body motion, and hip fractures

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occur most frequently in association with lateral falls. Video observations of naturally occurring falls in older people have detected particular problems in controlling lateral balance responses during sideways falls. An increased stride width is also a common feature of elderly gait and may be associated with the fear of falling and may be predictive of falls. Taken together, these observations emphasize that older individuals may be particularly vulnerable to postural balance instability and falls involving the lateral plane of motion.

The top panel of Figure 1 illustrates the problem of controlling lateral postural balance stability while standing.

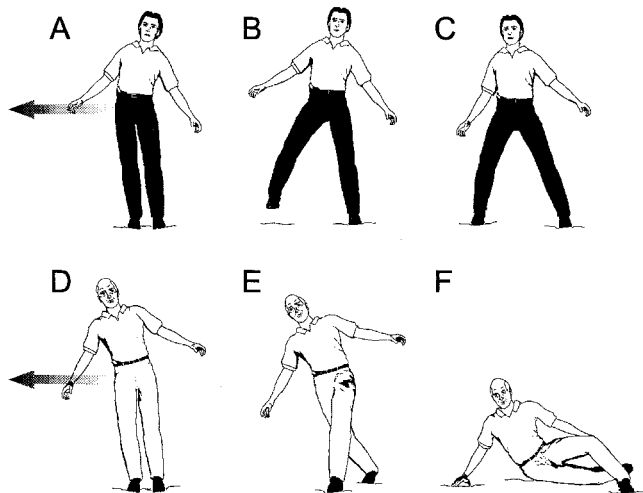
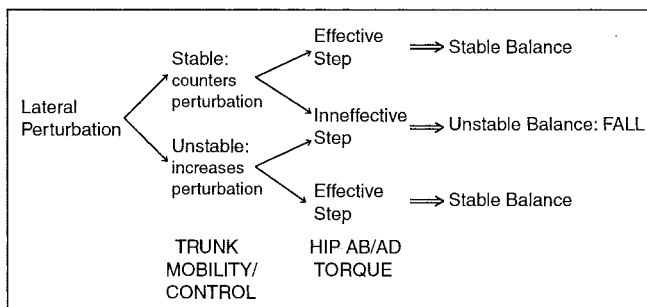


Figure 1. An illustration of the problem of controlling lateral postural balance through protective stepping. Upper panel. The outcome to a lateral waist-pull perturbation depends on two main hypothesized neuromusculoskeletal factors. The first factor, trunk mobility and postural control determining lateral motion of the trunk, either could counteract or increase the effects of the perturbation, depending on the initial direction and extent of lateral inclination of the trunk. The second factor, hip abduction-adduction (AB/AD) muscle torque capacity influences the stepping strategies selected by the subject and his effectiveness in sustaining standing stability. For single-step recovery solutions, subjects either could select a side-stepping strategy involving a series of interlimb hip abduction-adduction torques for limb loading and unloading or could select a crossover stepping strategy that complicates the trajectory of the limb and could increase the risk of falls resulting from collisions between the limbs. Depending on these two main factors, subjects may regain stable balance or may undergo an unstable balance state. This latter case would require additional steps or may lead to a fall. A–F. In response to a waist-pull perturbation to one side (leftward arrow in A and D), younger adults typically use a single side-stepping strategy in the direction of the perturbation (A–C), whereas older subjects more often use a crossover stepping strategy that, if ineffective in the worst-case situation, more likely may lead to a fall (D–F).

When a lateral pulling perturbation occurs (Fig. 1A,D), depending on the mobility and postural control of the trunk, a lateral tilt of the trunk either counters the direction of perturbation and thus minimizes its effects (stable), or moves with the perturbation and thus increases its effects (unstable). Furthermore, the perturbation causes a passive increase in load beneath the lower limb nearest to the side of the destabilization with a concomitant reduction in load of the opposite limb. Two primary single-step recovery solutions are available, depending on the hip abduction-adduction torque capacity of the subject. A sidestepping strategy requires the generation of a series of interlimb hip abduction-adduction torques to overcome the lateral perturbation and to unload the passively loaded limb (Fig. 1B) to execute a single sideways step in the direction of the perturbation. Alternatively, a crossover strategy involving the passively unloaded limb requires a more complex step limb trajectory and greater axial transverse motion to cross either in front of or behind the single stance limb (Fig. 1E). Either of these stepping strategies could be effective in lateral stabilization by extending the width of the BOS in relation to the moving COM (e.g., Fig. 1C). If ineffective stepping occurs, unstable balance may require additional steps or may lead to a fall (e.g., Fig. 1F). Movements of the arms frequently precede and accompany both patterns of protective stepping (Fig. 1A–F).

Because of impaired mobility, postural control of trunk motion, or both, and diminished hip torque-time generating capacity with aging, older subjects may have greater difficulties in compensating for a lateral perturbation. If the lateral perturbation exceeds the active limb loading and unloading ability and induces a lateral tilt of the trunk toward the side of the perturbation, then it would be easiest to move the passively unloaded limb by selecting a crossover stepping strategy (or a short medial step followed by additional steps). However, crossover stepping would increase the risk of collisions between the limbs and the probability of falls. Figure 1D–F illustrates this worst-case situation.

In summary, the normal control of postural balance in the lateral direction during stepping and walking is mainly achieved by M-L control at the hip joints for limb loading and unloading, coupling between the pelvis and trunk segments, and the spatiotemporal placement of the stepping foot. Thus, the neuromuscular control, coordination, and torque-time generating capacity of the interlimb hip abductor-adductor musculature in interaction with trunk motion control are crucially involved with each of the major mechanisms for sustaining sideways postural balance.

PROTECTIVE STEPPING: A FRAMEWORK FOR INVESTIGATING THE MOTOR CONTROL OF BALANCE

From a motor control perspective, protective stepping represents an attractive framework for identifying changes in control processes that may underlie impaired balance function and falls in older people. During imbalance, stepping represents a commonly executed protective option available to an individual that may precede rapidly extending the arms to absorb the impact of a fall, or grabbing nearby objects to

slow the rate of falling. Protective stepping may be initiated voluntarily in anticipation against a fall, or induced reactively by sensorimotor events in response to external perturbations to balance. Contrary to traditional views, reactively triggered stepping may be initiated well before the COM reaches the limits of the BOS (8,10). Importantly, older individuals, particularly those who experience falls, have an increased reliance on stepping to maintain balance rather than feet-in-place control strategies. An emerging body of work has begun to demonstrate and elucidate age-related changes in the initiation and execution of stepping, whether generated in response to a voluntary reaction time stimulus cue, or triggered by an externally applied physical perturbation of balance.

Lateral Stability During Protective Stepping

As a control problem, stepping requires that the central nervous system regulate the spatial and temporal relationship between the position and motion of the COM in interaction with the changing BOS. The transition from stationary standing to stepping requires the lateral transfer of body weight support. During stationary bipedal standing, the M-L COM position generally is centered above the BOS area between the feet. Lifting one foot to advance a step markedly reduces the BOS to the area of the single supporting foot. Without postural corrections, the body abruptly would begin to fall toward the unsupported side. For voluntary stepping (8,11,14), anticipatory postural adjustments (APAs) propel the COM toward the single support side before lifting the limb through an active redistribution of the ground reaction forces acting on the body in the frontal plane. Thus, M-L APAs normally minimize the tendency for the body to fall laterally at liftoff. In contrast, APAs often are absent or diminished in effectiveness during externally induced protective stepping (8,12), and this appears to compromise M-L stability. For either voluntary or induced stepping, the ongoing control of lateral balance during the single support phase mainly is achieved through M-L hip joint torque, regulation of frontal plane motion of the trunk through the lateral trunk musculature, and fine adjustments of the center of pressure location beneath the supporting foot via M-L ankle joint moments (7,8,12). Subsequently, the M-L placement of the foot relative to the COM position is another important factor affecting balance control in the frontal plane during stepping. Additionally, the speed of stepping will influence the requirements for M-L stabilization by affecting the duration of the single support period.

Voluntary Stepping

The ability to respond rapidly and effectively to environmental stimuli with stepping movements is vitally related to an individual's ability to maintain standing stability and to avoid falls in the everyday environment. In comparison with younger adults, studies of reaction time in stepping in older people typically have observed a delay in step initiation and execution timing (8,11,14). Furthermore, the initiation timing delays involve prolonged postural (M-L APA) and locomotion (stepping) phases, suggesting that a longer lateral weight transfer time jeopardizes the ability of older people to recover balance in time-critical situations.

Externally Induced Stepping

Using stepper-motor controlled waist-pulls applied at different magnitude combinations of pulling displacement, velocity, and acceleration in the forward direction, we have observed a remarkable similarity in most of the first step limb and whole body kinematics in the sagittal plane between younger adults and healthy community-living older nonfallers and fallers (12). Nevertheless, older subjects stepped more often and for smaller magnitudes of balance perturbation and showed a greater incidence of multiple stepping trials versus single-step recovery trials (10). Only the duration of the first step was found to be longer among the older faller group. This suggested that the increased time spent in single limb support increased the demands for lateral balance control for the older subjects who had been experiencing falls before the study.

In the frontal plane, the COM motion at the time of foot liftoff was similar among the groups. In contrast, at foot contact, the fallers displayed significantly greater COM displacement (Fig. 2A) and velocity (Fig. 2B) toward the stepping side and a more laterally directed foot placement (Fig. 2C) compared with the young and older nonfallers. Significant correlations between COM motion and foot placement suggested that stepping was adapted to match the lateral movement of the COM. Because the expected diminution in M-L APA characteristics during induced stepping, compared with volitional stepping, was equivalent among younger and older individuals, including elderly fallers, it is unlikely that the aging differences we observed in controlling lateral stability were attributable to differences in anticipatory postural mechanisms related to weight transfer as suggested for voluntary stepping.

This main difference in controlling lateral body motion during induced stepping suggested that the fallers included a wider step to compensate for the instability that developed between liftoff and foot contact. However, because the direction of destabilization was known in advance, the fallers also might have preplanned a lateral foot placement to compensate for lateral instability, for anxiety about falling, or both. Findings that older nonfallers who take multiple forward or backward steps in responding to platform perturbations are more likely than younger subjects to direct their ongoing steps more laterally also would appear to indicate difficulties with controlling lateral stability during protective stepping (8).

In response to directly lateral disturbances of stance (3) with the side of perturbation uncertain, younger individuals generally use a single lateral step of the loaded limb (Fig. 3A,B) to extend the BOS and to arrest the motion of the falling COM (see Fig. 1A–C). The older subjects who had not been experiencing falls more often took multiple steps that typically included an initial crossover step (Fig. 3A,B) with the limb that was unloaded passively by the perturbation (see Fig. 1D–F). During the crossover steps, the data from 20 subjects included a total of 12 collisions between the limbs involving 7 of the 10 older subjects compared with one collision in a younger subject. After platform translations (8), findings indicating that older subjects predominantly used a sidestepping sequence initiated with the unloaded limb,

form tests regardless of whether a crossover or side-step sequence is used.

NEUROMUSCULOSKELETAL FACTORS RELATED TO LATERAL STABILITY

Although age-related changes in neuromusculoskeletal systems and their relationship to impaired balance function and falls long have been recognized, the predominant focus of investigation has centered on the control of lower limb muscle force or torque and joint motion affecting balance in the anteroposterior direction. The sagittally oriented joint torques and ranges of motion needed for forward-backward stepping likely are to be well within the capabilities of most healthy community-living older people (6,8). Thus, neuromusculoskeletal changes generally are not considered problematic for initiating protective stepping because first step characteristics are frequently comparable between young and old (6,8,12). However, aging impairments in the ability to generate rapid and appropriately controlled muscular forces, joint torques, and postural movements involving the M-L hip joint adductor-abductor musculature and decreased mobility and control of the trunk segment may compromise lateral stability and balance function during protective stepping in several ways. First, the M-L hip muscles contribute to generating APAs for lateral weight transfer as previously described. Second, hip abduction torques are normally generated on the upcoming single stance side before and accompanying step limb liftoff (7,8). These joint torques serve an important stabilizing role of the pelvis and trunk during step execution similar to ongoing gait. Third, M-L foot placement achieved by hip abduction-adduction control during stepping is a crucial component of frontal plane balance recovery (7,8,12). Fourth, postural movements of the trunk involving frontal and transverse plane rotation in interaction with similar directions of pelvic motion are normally engaged in stabilizing the body against disturbance to balance in the frontal plane (1,7).

We have determined that M-L hip abductor-adductor torque-time capacity may be impaired with aging (4). In comparison with younger women, the isometric peak torque of older women was reduced significantly: by 35% for hip abduction and by 21% for hip adduction. Decreases with age also were significant for isometric rates of torque for both muscle groups. More striking were the changes that were found for concentric isokinetic peak torque assessments ($60^\circ\cdot s^{-1}$) of the hip abductor and adductor muscle groups that showed declines of 43% and 54%, respectively (Fig. 4). These decrements in hip torque production likely would become even more marked at higher velocities. In this regard, we observed that the older women tested in our studies were not able to generate torque consistently at a velocity of $90^\circ\cdot s^{-1}$. These data are consistent with the observation that severe type II fiber atrophy of the gluteus medius, an important hip abductor muscle, is an independent risk factor for hip fractures resulting from falls in elderly women (15).

Impairments in axial mobility or the control of axial-trunk motion resulting from aging may represent additional complications for maintaining lateral stability during protective step-

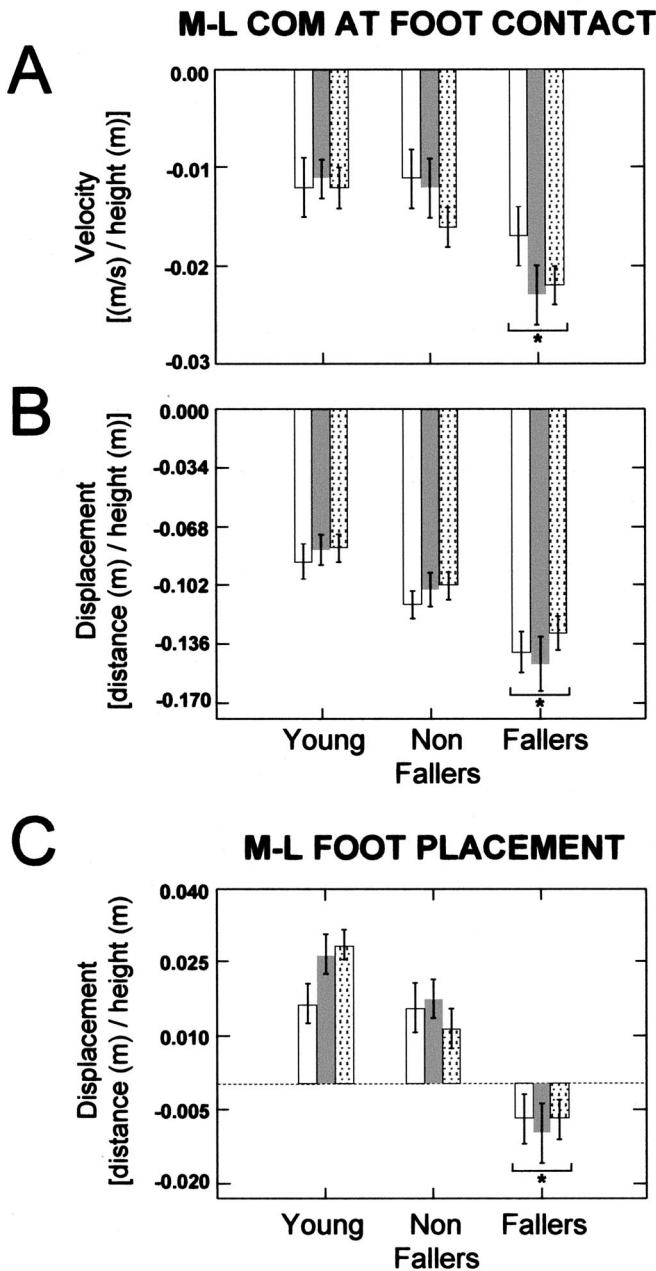


Figure 2. Group mean values \pm 1 SEM for mediolateral (M-L) body center of mass (COM) velocity (A), displacement (B), and M-L foot placement (C) at the instant of first step foot contact during forward induced stepping at small (white bars), medium (gray bars), and large (dotted bars) waist-pull perturbations of stance. In (A) and (B), negative values are in the direction of the stepping side, and in (C), negative values are away from the mid sagittal line of the body. *Significant differences ($P < 0.02$ to $P < 0.001$, ANOVA) between fallers ($n = 18$) versus nonfallers ($n = 20$) and young ($n = 12$). Modified from (12).

whereas younger subjects responded more often with crossover steps, suggest that the lateral stepping strategies used by younger and older subjects also may depend on the form of perturbation used, that is, whether external disturbances of postural balance are applied either near the COM or at the level of the BOS where changes in ground reaction forces are occurring. The chief difference between methods is that subjects appear to step first with the unloaded side for plat-

Lateral Stepping Characteristics

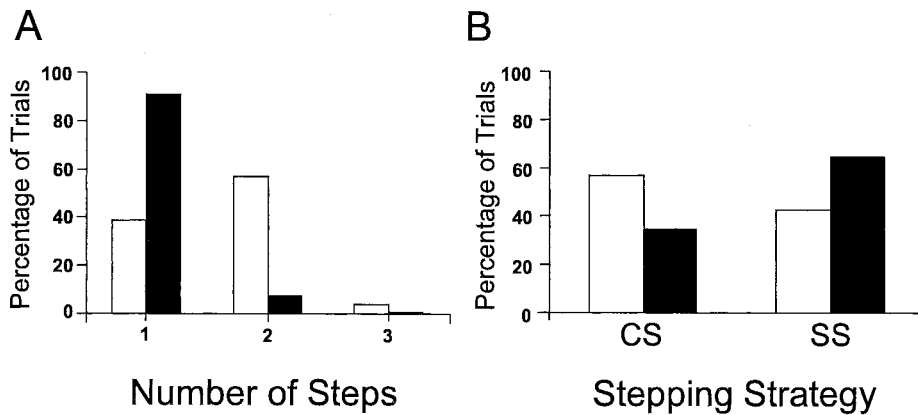


Figure 3. Group mean percentages of trials in which older subjects ($n = 10$; lighter bars) and younger subjects ($n = 10$; darker bars) (A) executed one or multiple steps to regain balance after lateral waist-pull perturbations of stance or (B) used crossover steps (CS) versus side steps (SS) to regain balance. Between-group differences were statistically different ($P \leq 0.001$, χ^2). Data from (3).

ping. For example, examination of extensive clinical data on physical characteristics, self-assessment scores, sensorimotor and neuromusculoskeletal performance variables, and functional measures of balance and gait for the same and additional older individuals who demonstrated reductions in hip abductor–adductor muscle torque-time capacity, revealed that limitations in active axial rotation combining the transverse and frontal planes were among the most important variables that discriminated poorer performance of clinical tests of balance and gait functions (9). These associations also classified the subjects into two distinct cluster groups of older subjects who performed either more or less like younger individuals on the same functional measures of balance and gait performance. These observations are compatible with a recent report indicating that directionally specific limitations of trunk roll movements after multidirectional tilting perturbations of the support surface contributed to lateral instability among older individuals (1).

Each of the foregoing neuromusculoskeletal changes with age has the potential to impair significantly the effective coupling between pelvic and axial-trunk motion that must normally adapt to challenges to postural balance in the lateral direction. With respect to Figure 1, the effective use of a sidestepping strategy crucially depends on rapid alterations in interlimb hip abductor–adductor torque generation for unloading and loading followed by a rapidly directed and scaled lateral foot placement controlled by motion of the hip joint. Concurrently, an initial counter-rotation of the trunk in the frontal plane away from the direction of perturbation (Fig. 1A) and ongoing regulation of axial motion laterally and transversely (Fig. 1B,C) contribute to effective balance recovery. We propose that impaired hip abductor–adductor torque-time generation and axial-trunk mobility and control may predispose many older people to use a crossover stepping strategy. Although selecting the limb that initially is passively unloaded by the perturbation likely reduces the step initiation timing, this potential advantage is countered by the longer and relatively more complex foot trajectory associated with the increased risk of collision with the stance limb. Furthermore, in comparison with sidestepping, crossover step-

ping generally increases the time spent in the unstable single-limb support phase (8).

POSSIBLE APPLICATIONS FOR REDUCING THE RISK OF FALLS IN OLDER PEOPLE

Although addressing identified risk factors for falls through a variety of interventions, including exercise programs, has begun to demonstrate some benefit in the prevention of falls (2), specific attention to intervention strategies focused on the problem of lateral instability has not been forthcoming. This would appear to be an important area for focusing physical rehabilitation interventions. For example, exercise programs that emphasize rapid contractions of the hip abductor–adductor musculature in load-bearing situations through isolated joint training as well as during more functionally relevant weight-bearing situations should be applied. It also may be possible to improve lateral stability through the repetitive use of induced stepping and step-practice training protocols (13) that emphasize rapid changes in limb loading and unloading during voluntary and reactive stepping involving multiple directions. We also have been struck by the observation that improvement in the efficiency of protective stepping through reduction in the number of multiple steps needed for balance recovery by older individuals often occurs within a single session of repetitive multidirectional waist-pulls. This reduced tendency to execute multiple stepping reactions and the further observation that many older individuals appear to switch from a crossover to a lateral stepping strategy with repetitive forced step training, suggests the possibility of enhancing balance function through adaptive changes in protective stepping mechanisms (13,14). Finally, it presently is unclear whether age-associated limitations in axial-trunk mobility involving rotation in the frontal and transverse planes are the result of changes in the passive properties of musculoskeletal structures or of difficulties with actively controlling movement of the trunk or reflect a strat-

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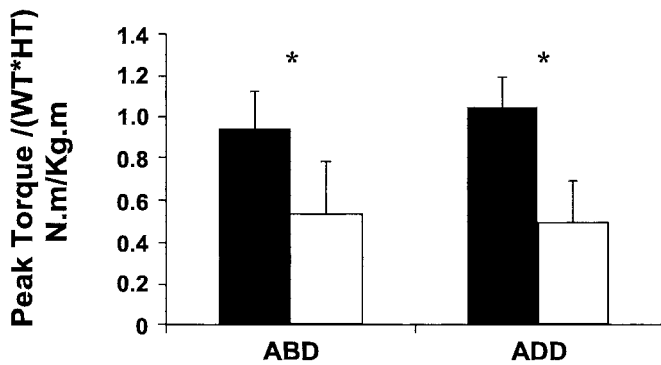


Figure 4. Group mean isokinetic peak torques ($60^{\circ}\cdot s^{-1}$) + 1 SD normalized by subject weight (*WT*) and height (*HT*) for hip abduction (*ABD*) and adduction (*ADD*) in younger ($n = 38$; darker bars) and older ($n = 38$; lighter bars) women. The older women had significantly less average isokinetic peak torque ($P < 0.001$, ANOVA) with 43% less hip strength in ABD and 54% less in ADD than the younger women. Data from (4).

egy used to constrain the motion of the trunk. However, evaluating and optimizing axial-trunk rotational mobility, control, or both would seem to be important considerations for postural balance stability in the lateral direction.

SUMMARY

Older individuals in general, and those who are at a greater risk of falling in particular, may be especially vulnerable to instability in the lateral direction during protective stepping and other balance-correcting functions. It is proposed that specific impairments of neuromusculoskeletal factors related to axial-trunk rotational mobility, postural control, and M-L hip muscle force and torque-time production disrupt key control functions for maintaining effective lateral stability. These changes with age may provide insight into motor control mechanisms underlying falls in older people and highlight the need for therapeutic interventions that focus on the problem of lateral instability.

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