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Age and gender differences in peak lower extremity joint torques and ranges of motion used during single-step balance recovery from a forward fall

Laura A. Wojcik[a,*], Darryl G. Thelen[a,1], Albert B. Schultz[a,b], James A. Ashton-Miller[a,b], Neil B. Alexander[b,c]

[a]*Department of Mechanical Engineering and Applied Mechanics, University of Michigan, Ann Arbor, MI 48109-2125, USA*
[b]*Institute of Gerontology, University of Michigan, Ann Arbor, MI 48109-2125, USA*
[c]*Department of Internal Medicine and Ann Arbor VA Medical Center GRECC, University of Michigan, Ann Arbor, MI 48109-0926, USA*

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Abstract

Previous studies have found substantial age and gender group differences in the ability of healthy adults to regain balance with a single step after a forward fall. It was hypothesized that differences in lower extremity joint strengths and ranges of motion (ROM) may have contributed to these observed differences. Kinematic and forceplate data were therefore used with a rigid-link biomechanical model simulating stepped leg dynamics to examine the joint torques and ROM used by subjects during successful single-step balance recoveries after release from a forward lean. The peak ROM and torques used by subjects in the study were compared to published estimates or measured values of the available maxima. No significant age or gender group differences were found in the mean ROM used by the subjects for any given initial lean angle. As initial lean angle increased, larger knee ROM and significantly larger hip ROM were used in the successful recoveries. There were substantial gender differences and some age group differences in peak lower extremity joint torques used in successful recoveries. Both young and older females often used nearly maximal joint torques to recover balance. Subjects' maximum joint strengths in plantarflexion and hip flexion were not good predictors of single-step balance recovery ability, particularly among the female subjects. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Rates of falls and serious fall-related injuries vary substantially with both age and gender among adult populations (Schultz et al., 1997), but little is known about the biomechanical factors that might lead to these differences. Previous studies have indicated that overall mobility, fall propensity, and balance recovery abilities can be predicted by declines in lower extremity strength (Brown et al., 1995; Duncan et al., 1993; Gehlsen et al., 1990; Grabiner et al., 1993; Wolfson et al., 1995). A nonlinear relationship between declines in lower extremity strength and gait speed, a general measure of mobility performance, has also been reported (Buchner et al., 1996). Age-related strength deficits have been demonstrated in healthy subjects at the ankle (Thelen et al., 1996) and the quadriceps (Fisher et al., 1990), and healthy older females tend to exhibit even smaller maximal lower extremity torques than do older males (Hakkinen et al., 1996; Hurley, 1995; Schultz, 1992).

Given the possible relationship between strength and the tendency to fall, age-related declines in maximum joint torques may contribute to the high incidence of falls among the elderly. Two earlier reports from our laboratory (Thelen et al., 1997; Wojcik et al., 1999) documented significant age and gender group differences in the abilities of healthy adults when regaining standing balance with a single step after an induced forward fall, with older females exhibiting the poorest recovery performance of any group tested. Given that the age and gender-related

* Corresponding author. Department of Engineering Science and Mechanics, Mail Code 0219, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA. Tel.: + 1-540-231-7979; fax: + 1-540-231-4574.

[1] Dr. Thelen is currently at the Department of Physics and Engineering, Hope College, Holland, MI, USA.

E-mail address: wojcik@vt.edu (L.A. Wojcik).

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differences in reaction time were too small to explain these significant differences in performance, it was hypothesized that age-related declines in joint strengths may have contributed to older subjects' inability to effect single-step recoveries. Given older adults' concomitant loss in lower extremity flexibility (Schultz, 1992), it was also hypothesized that age-related declines in lower extremity range of motion (ROM) may have also contributed to older adults' inability to recover from larger perturbations. The present report therefore provides additional data from the forward fall experiments and biomechanical analyses of those data, including analyses of age and gender group differences in the peak joint torques and ROM used to recover balance, comparisons of peak torques and ROM with literature data and measurements of subjects' maximum available torques, and correlations between subjects' measured maximum available torques and balance recovery abilities.

2. Methods

Methods already reported (Thelen et al., 1997; Wojcik et al., 1999) are reviewed here only briefly. Methods unique to the present analyses will be described in more detail. All of the procedures in this study were approved by The University of Michigan Institutional Review Board.

Twenty female and 20 male subjects participated, with 10 young and 10 older (mean ages of approximately 25 and 72 y) subjects in each gender group. Young subjects were recruited from within the University community. Older subjects were independently dwelling members of the community. Older subjects were given a standardized medical examination in order to confirm the absence of notable musculoskeletal, neurological or otological disease. All subjects reported that they were right-handed and right-footed. Height, weight, and lower extremity anthropometric measures were recorded for all subjects.

Lower extremity strengths were tested with the subjects in a recumbent position, supported by handles and straps sufficient to allow them to develop their full strengths. Both isometric and isokinetic strengths were measured in left ankle plantarflexion and right hip flexion. During the isometric tests, subjects were instructed to push "as hard and as fast as possible" for 3 s after either a visual or spoken cue. Isokinetic tests were conducted at 120°/s, using the same instructions and cueing procedures as for the isometric tests. Subjects were given at least one practice trial, and data were then recorded for two trials of each task. Male subjects were tested using a MERAC® (Universal Gym Equipment, Cedar Rapids, IA) isokinetic dynamometer, while female subjects were tested on a BioDex® (Biodex, Inc., Shirley, NY) system. Peak torques were recorded using in-house software for the MERAC system and manufacturer-supplied software for the BioDex. All statistical analyses were performed using the largest torque exerted by each subject at each joint. No statistical analyses were made to examine gender differences in peak torques within age groups because of the equipment difference between the two gender groups.

In the forward falls tests, a horizontal lean-control cable attached to the back of a pelvic belt supported each subject in a forward-leaning position. Subjects were instructed to keep their heels in contact with the floor and to keep the same amount of weight on each foot while being supported. The magnitude of each lean was determined by measuring the percent of body weight (%BW) supported by the lean cable. All subjects wore a full-trunk safety harness suspended from an overhead track that allowed for forward and lateral motion while preventing contact of any body part, other than the feet, with the ground. Subjects were instructed to regain their balance by taking a single step with their right foot after each fall was initiated. Falls were induced by releasing the lean control cable after a random time delay.

The first attempted balance recovery was after release from a lean held at 15 %BW. To find the maximum initial lean angle from which balance could be recovered as instructed, leans were successively increased by 5 %BW until a subject failed to recover balance twice at that lean magnitude. Failures were defined as: (1) trials where the subject took a second step with the left foot whose horizontal length exceeded 30% of body height; and (2) trials in which at least 20% of the subject's weight was applied to the safety harness.

Data were collected for lower extremity body segment motions, foot-floor reaction forces and moments, and support cable loadings. Data collection was initiated 500 ms prior to releasing the subjects from their initial leans, with a sampling rate of 100 Hz over the three second trial. Foot-floor reactions were measured with two AMTI® (Watertown, MA) force platforms located under the subject's feet in the initial lean configuration. Termination of the first recovery step was detected by a switchplate located forward of the subjects. Force transducers were used to monitor lean control and safety harness cables loads.

Three-dimensional kinematic data were recorded with an Optotrak® (Northern Digital Inc., Waterloo, Ontario) optoelectronic motion analysis system. Infrared-emitting diodes were placed over landmarks on the right-hand side of the subjects' bodies, including the fifth metatarsal head, heel, lateral maleolus, fibula head, lateral femoral epicondyle, midthigh, humeral head, and tragus. Additional diodes were placed on the left leg at the medial metatarsal, heel, medial maleolus, and tibial head. A fixed global reference frame was defined using three diodes attached to the force platforms. Kinematic data were filtered forwards and backwards through a sixth-order low-pass Butterworth filter that had a cutoff frequency of

6 Hz. A five-point differentiation scheme was used to calculate linear and angular velocities and accelerations of each body segment from the diode position data (Wojcik, 1997).

Maximum joint excursions during each recovery were calculated for the ankle, knee and hip of the swing leg using joint angle histories derived from the measured body segment kinematics. The ROM used were calculated as the differences between the largest and smallest of these angles.

For the inverse dynamics model, anthropometric data were scaled to each subject's body mass and height, using segmental mass and center of mass data assembled from the literature (Chaffin and Andersson, 1991). The model of the stepped leg used rigid links for the foot, the lower leg, and the upper leg, with the upper leg attached to a single head-arms-trunk segment (Wojcik, 1997). These links were assumed to be connected with frictionless pin joints. The muscles crossing each joint were represented in total by a single torque generator. Sagittal-plane peak joint torques and peak rates of torque development from successful single-step recoveries were calculated in both flexion and extension at the ankle, knee and hip of the stepped leg. These calculations were made by combining measured forceplate and kinematic data with scaled anthropometric data and the governing Newton–Euler equations of motion. Torques were calculated during the time interval between release of the lean control cable and first landing of the stepped foot.

Analyses of peak joint torques used during the last successful single-step balance recovery were performed at each lean magnitude. Separate analyses of variance, both one-way and two-way, were used to determine the effects of age and gender on these quantities. Age differences within gender groups were determined using independent sample *t*-tests. Individual analyses were made at each lean magnitude to determine whether the significance of age or gender effects changed during recoveries from larger lean magnitudes. Torques used in the successful recovery from the largest lean were compared with either maximum measured values or those available in the literature (Schultz, 1992). The measured peak torques available to each subject were linearly regressed with the maximum lean magnitude for successful fall recovery, and the coefficient of determination was calculated. Because of the two different brands of equipment used for the strength measurements, these regressions were made separately across the two gender groups, rather than across all subjects.

Table 1
Strength test results: mean peak joint torques (Nm) available for left ankle plantarflexion and right hip flexion[a]

	Young men	Older men	Young women	Older women
Ankle plantarflexion				
Isometric mean[b]	181 (39)	122 (38)	94 (23)	79 (21)
Isokinetic mean[c]	105 (27)	77 (18)	35 (19)	26 (15)
Hip flexion				
Isometric mean[d,e]	188 (42)	141 (38)	73 (12)	52 (13)
Isokinetic mean[f,g]	165 (22)	105 (24)	66 (16)	40 (12)

[a]Gender differences were not tested for statistical significance because different strength-testing equipment was used for female and male subjects. Standard deviations in parentheses.
[b]$p = 0.003$, for age differences among men.
[c]$p = 0.02$, for age differences among men.
[d]$p = 0.014$, for age differences among men.
[e]$p = 0.001$, for age differences among women.
[f]$p < 0.001$, for age differences among men.
[g]$p = 0.001$, for age differences among women.

3. Results

Young females developed significantly larger mean joint torques in hip flexion than did older females in both isometric and isokinetic tests ($p = 0.001$, Table 1). No statistically significant age group difference existed in mean ankle plantarflexion strengths among female subjects. Young males were significantly stronger than older males in isometric and isokinetic ankle plantarflexion ($p < 0.05$) and hip flexion ($p < 0.02$).

At any given lean magnitude, all four subject groups used, in the mean, approximately the same stepped-leg ankle, knee and hip joint range of motion (ROM) during their recoveries (Fig. 1). As lean magnitude increased, the ankle ROM used remained approximately constant, at approximately one-half or less of the estimated available ROM. In contrast, the utilized knee and hip ROM increased as lean magnitude increased, approaching the estimated maximum available ROM at the largest lean magnitudes. The young adults ultimately used substantially larger hip ROM than did the older adults as a result of this increase at the larger lean magnitudes.

Across lean magnitudes, the ankle and knee joint torques used for successful recoveries were nearly constant (Fig. 2). In contrast, the knee flexion torques used by the young males increased significantly ($p = 0.004$) with increasing lean magnitude, but the magnitude of that increase was small. Hip flexion torques increased significantly with increasing lean magnitudes for young males ($p < 0.001$), older males ($p < 0.001$), and young females ($p = 0.005$). Hip extension torques used by the young males also increased significantly ($p < 0.001$) with increasing lean magnitude. The largest hip flexion and extension torques used by the young males were substantially larger than those used by the other groups.

When the magnitudes of maximum successful fall recoveries were linearly regressed with measured available peak joint torque strengths in ankle plantarflexion and

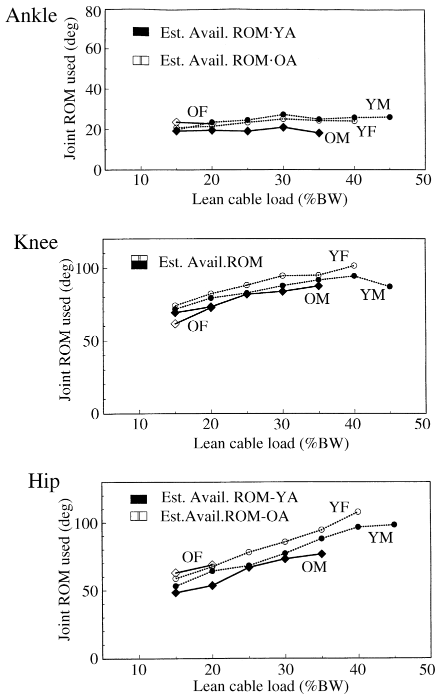

Fig. 1. Mean lower extremity range of motion (deg) used during successful balance recoveries at each lean magnitude. (OA) = older adults; (OF) = older female subjects; (OM) = older male subjects; (YA) = young adults; (YF) = young female subjects; (YM) = young male subjects. The estimates of the ranges of motion (ROM) available were made from reports in the literature.

hip flexion (Tables 2, 3, Fig. 3), coefficients of determination ranged from 0.087 to 0.177 among the female subjects and from 0.012 to 0.412 among the male subjects. While the two measured maximum strength capacities therefore explained as much as 41% of the variance in the maximum lean angle achieved by older males, they explained with a positive correlation coefficient less than 5% of the variance in the older females.

4. Discussion

We hypothesized that age-related declines in muscular strength would be associated with older adults' diminished capabilities in recovering balance after a forward fall. The low levels of correlation between maximum volitional strength and maximum successful lean magnitude do not fully support this hypothesis. Older females exerted the largest ankle plantarflexion torques of any subject group during their fall recoveries, and yet they were the least able to succeed with a single step. Given that the female subjects who participated in the current study were generally shorter and lighter than male subjects, normalizing the calculated joint torques to the product of weight times height only emphasizes the observed gender-related disparities in joint torque.

We also hypothesized that older adults' smaller lower extremity range of motion (ROM) would contribute to their inability to effect single-step balance recoveries. At

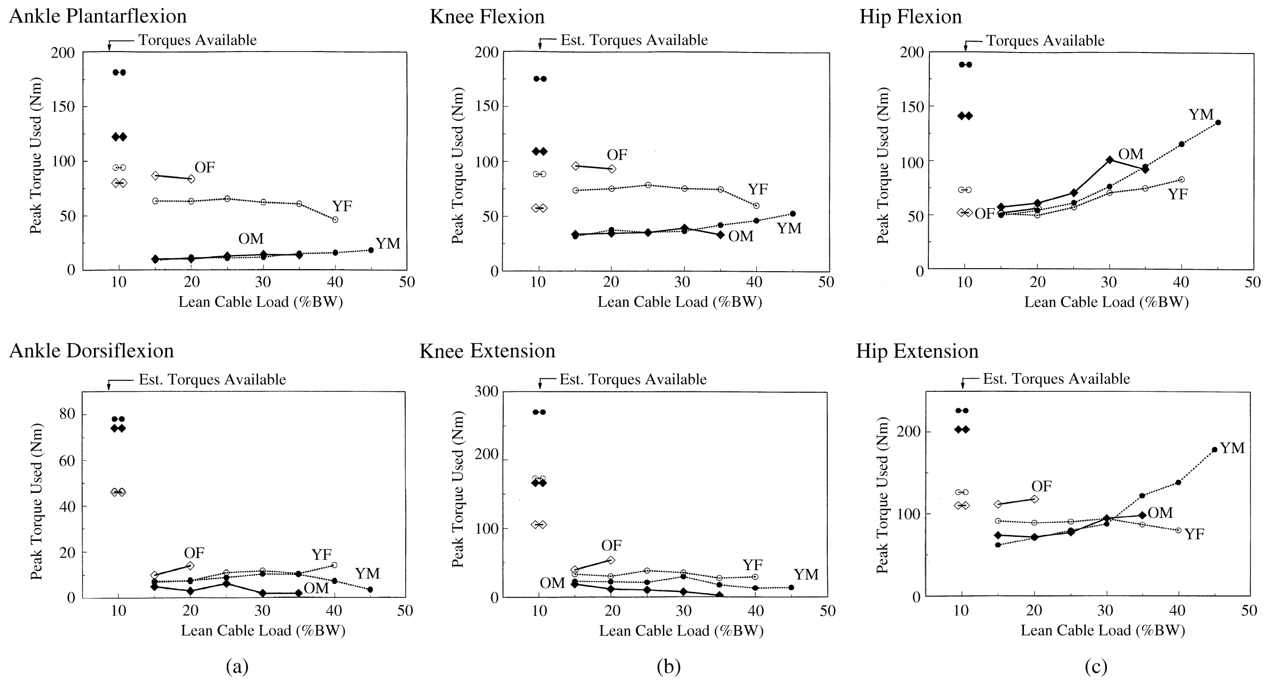

Fig. 2. Mean lower extremity peak joint torques (Nm) used during successful balance recoveries at each lean magnitude. The abbreviations used are the same as those described in the Fig. 1 legend. The torques available in ankle plantarflexion and hip flexion were the mean torque strengths measured for the subjects. For the other torques, the estimated (Est.) available were derived from reports in the literature (Schultz, 1992).

Table 2
Coefficients of determination (r^2) for linear correlations between mean peak joint torques available in left ankle plantarflexion and right hip flexion with maximum successful lean magnitudes — within subject groups[a]

	Young men	Older men	Young women	Older women
Ankle plantarflexion				
Isometric strength	0.284	0.412[b]	0.160[c]	0.083[d]
Isokinetic strength	0.185	0.268	0.020[c]	0.091[d]
Hip flexion				
Isometric strength	0.012	0.284	0.117	0.054[d]
Isokinetic strength	0.169	0.377[c]	0.177	0.045

[a]Correlations are within each of the four subject groups, and so indicate whether strength discriminates among individuals' maximum leans within those groups. Fig. 3 shows correlations within each of the two gender groups, with those groups including both young and older adults. Because young adults recovered from larger leans and were stronger, the Fig. 3 correlations are stronger ones.
[b]$p < 0.05$.
[c]$p < 0.06$.
[d]Denote negative r-values.

Table 3
Coefficients of determination (r^2) for linear correlations between mean peak joint torques available in left ankle plantarflexion and right hip flexion with maximum successful lean magnitudes — within gender groups[a]

	Males	Females
Ankle plantarflexion		
Isometric strength	0.600[b]	0.036
Isokinetic strength	0.411[b]	0.037
Hip flexion		
Isometric strength	0.329[b]	0.357[b]
Isokinetic strength	0.665[b]	0.469[b]

[a]Correlations are within each of the two gender groups. These are the r-square values that correspond to the linear regressions shown in Fig. 3. The wider ranges of strength and performance present with the inclusion of both young and old data make these correlations stronger than those within individual subject groups, as presented in Table 2.
[b]Indicate statistical significance ($p < 0.01$).

maximum lean magnitudes, the knee and hip ROM used by the young adults were substantially larger than those used by the older adults. Despite these observed differences, literature data for available ROM (Schultz, 1992) indicate that the older adults did not appear to use the full ROM available to them. This discrepancy suggests that ROM limitations may contribute to balance recovery capabilities only under extreme conditions.

There were clear gender differences in the magnitudes of the stepped-leg joint torques used for balance recovery. These differences were notable in terms of the absolute magnitudes of the torques used, and were quite marked in terms of the torques used relative to assumed

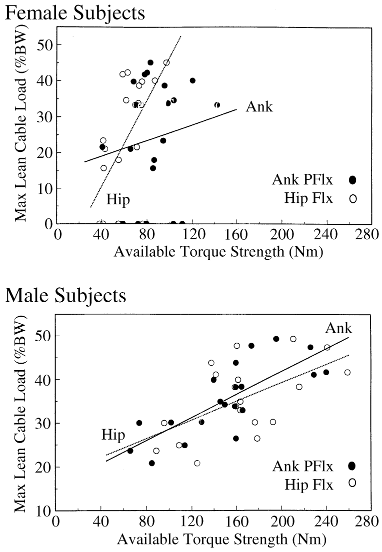

Fig. 3. Mean maximum lean magnitudes (%BW) for successful balance recoveries in relation to available ankle plantarflexion and hip flexion joint torque strengths (N m). Linear regressions of the relationships are shown. Note the data points on the horizontal axis for the five female subjects who did not recover balance as instructed from any imposed lean magnitude. Coefficients of determination are given in Table 3. Caution is needed in comparing outcomes of these regressions with those in Table 2, as noted in the Table 2 caption.

maxima. Given that young females also used larger plantarflexion torques than did young males, it appears that a gender-related disparity in muscle recruitment may be present in single-step recovery from a forward fall. The evidence for a gender-related strategy difference also includes the observation that young males' maximum torques in hip flexion become significantly larger than those of young females at large lean magnitudes. Young males' use of larger hip flexion torques may increase their stepping velocities at maximum successful lean magnitudes, which were significantly faster than those of either older males or young females. Despite the observed differences among young subjects' hip and ankle torques, no significant gender differences were found among young adults' maximum lean magnitudes from which balance could be recovered by taking a single step (Thelen et al., 1997; Wojcik et al., 1999).

There were clear age differences within the gender groups regarding the magnitudes of the stepped-leg joint torques used to regain balance at maximum successful leans. The maximum hip flexion and hip extension torques used by the young males substantially exceeded those used by the older males. Neither the young nor older males, however, called fully upon their seemingly available strengths at any lean magnitude from which they succeeded in recovery. The maximum hip flexion torques used by the young females exceeded those used by the older females. Young females approached full use of their apparently available strengths only in ankle plantarflexion and knee flexion, while the older females used mean peak torques in ankle plantarflexion, knee flexion, hip flexion and hip extension that equaled or exceeded those assumed to be available. These age and gender group comparisons at maximum lean magnitudes need to be interpreted with care, however, given that the maximum lean magnitudes for the young adults were larger than those for the older adults, particularly those for the older females.

Comparing the torques used during successful balance recoveries to subjects' measured maxima or literature-estimated maximum joint torques (Schultz, 1992; Thelen et al., 2000; values indicated in Fig. 2), all four subject groups used, in the mean, modest stepped-leg ankle dorsiflexion and knee extension torques. The maximum ankle plantarflexion, knee flexion, hip flexion and hip extension torques used by the two male groups were generally low. The young females used mean maximum torques in ankle plantarflexion, knee flexion and hip extension that were fairly large, but these maxima generally did not approach the measured or literature-estimated maximum available joint torques. At the larger lean magnitudes, young females used hip flexion torques that approached their assumed maxima. The older females used mean torques that equaled or exceeded assumed maxima in ankle plantarflexion, knee flexion, hip flexion and hip extension.

This study had a number of limitations. First is the small sample size, particularly given that only five older women were able to recover balance as prescribed from any imposed lean magnitude. We argue, however, that given our results for this small group of extremely fit older women, even larger age and gender differences would be apparent if a larger cohort of more "average" subjects was tested. Second, because of limitations on placement of the optoelectronic motion capture equipment, stance leg joint torques could not be assessed. Support limb dynamics might play an important role in single-step recoveries. Third, in the absence of strong nonlinear trends in the relationship between lower extremity strengths and performance variables, only linear regression analyses were used. Fourth, inverse dynamics model calculations of the type used in this study are subject to errors caused by inaccurate estimation of joint centers of rotation, use of population mean data to scale anthropometry, signal noise, and artifacts arising from the differentiation and filtering processes. The current inverse dynamics analyses used the same data collection equipment and the same differentiation and noise filtering routines for all four subject groups. Given that identical data collection and processing techniques were used for all subjects, relative age-group and gender-group differences in the biomechanical outcome variables should not have been substantially affected by errors in the calculations of absolute torque and ROM magnitudes.

The prescribed task of recovering balance by taking only one step with the right leg may have been less to the liking of the older adults compared to the young. In response to sudden waist pulls backwards during which subjects were not instructed as to how to respond, Luchies et al. (1994) and McIlroy and Maki (1996) found that young adults more often recovered balance by taking a single step, while older adults more often took multiple steps. Requiring older subjects to use a non-instinctive stepping strategy may have affected these subjects' single-step recoveries. Differences in non-biomechanical factors, such as in degree of motivation and level of fear, could also account for some of the age-related differences observed in balance recovery performance. Despite their limited performances, however, it has been argued (Wojcik et al., 1999) that the older females in the present study were just as highly motivated to succeed as the other groups.

It is possible that the two joint strengths tested here were not critical to recovery or that tests of maximum volitional strength are not good indicators of the strength available in time-critical balance recovery responses among healthy subjects. Perhaps, as suggested by Horak et al. (1989) and Hsiao and Robinovitch (1999), rather than having overwhelming deficits in any one measure of neurological or musculoskeletal fitness, older adults and other people at heightened risk of falling may instead suffer from small deficits in a large number of motor-related functions.

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