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Lower Extremity Strength Plays Only a Small Role in Determining the Maximum Recoverable Lean Angle in Older Adults

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Background. The purpose of this study was to determine the extent to which measures of lower extremity strength and power contribute to the ability of older men and women to restore postural equilibrium using a single-step recovery following a large postural disturbance.

Methods. The postural disturbance, which has been used as a surrogate for forward-directed falls, involved a sudden release from a forward-leaning angle. The ability to recover using a single step was evaluated as the maximum recoverable lean angle for 56 healthy older women and men. Maximum voluntary isometric and isokinetic strength was measured for ankle plantarflexion and dorsiflexion, knee flexion and extension, and hip flexion and extension. Discriminant analysis was used to determine the strength measures that best classified participants as members of the highest ($n = 14$) or lowest ($n = 14$) quartiles of maximum recoverable lean angle. Those variables were subsequently entered into a regression analysis to characterize the relationship between strength and maximum recoverable lean angle for the entire participant sample.

Results. Maximum isokinetic dorsiflexion strength at 90°/s satisfied the criteria of the stepwise discriminant analysis, and correctly classified 82.1% of the participants in the highest or lowest quartiles of maximum recoverable lean angle. The multiple regression procedure, performed on all participants ($n = 56$) revealed a significant quadratic relationship between maximum isokinetic dorsiflexion strength at 90°/s and maximum recoverable lean angle ($R^2 = 0.295$; $p < .001$).

Conclusions. Lower extremity strength makes a small, but significant contribution to maximum recoverable lean angle. However, because 70% of the shared variability remained unaccounted for, it is suggested that other performance factors, such as coordination, may be of greater importance to performance of this time-critical motor task.

THE risk of falls during locomotor activity is, in part, dependent on the ability to restore dynamic equilibrium following postural disturbances (1). Numerous laboratory protocols have implemented voluntary stepping tests and induced stepping tests that serve as surrogates for the types of postural disturbances that lead to falls in the community. The surrogate tasks thereby assess, or reflect, the ability of participants to restore dynamic equilibrium and avoid falling (2–4). The ability to perform successful stepping responses following these types of tests has been used as an indicator for the risk of falling (5,6).

Release from a forward-leaning position is commonly used to initiate forward-directed falls. When released from a forward-leaning position and instructed to restore stability using a single step, healthy older adults have a significantly smaller maximum recoverable lean angle than that of young adults (7). Furthermore, older women have significantly smaller maximum recoverable lean angles than do older men (8). These age- and sex-related findings have been attributed to the maximum lower extremity speed that may be attained during the recovery step. Maximum lower extremity speed is dependent on lower extremity muscle strength, although a substantial sex-related effect has been reported (3). Lower extremity strength accounted for about 40% of the variance in the maximum recoverable lean angle of older men but for less than 5% of the variance in the maximum recoverable lean angle of older women.

Two methodological issues may have influenced the above results (3). First, measures of strength were expressed in absolute force units. Between-sex differences in muscle strength are often reduced or eliminated when body size differences are considered (9–11). Second, the number of older women for whom data were available was relatively small ($n = 5$). The present study addressed these two issues and, in doing so, determined the extent to which measures of lower extremity strength contribute to the maximum recoverable lean angle in older men and women. Insofar as the published literature does not present a clear understanding of the specific lower extremity joints that are crucial to recovery from this type of postural perturbation (i.e., ankle, knee and/or hip; stepping leg and/or support leg) or, indeed, the contraction category (i.e, isometric, dynamic) and, under dynamic conditions (eccentric vs concentric) the contraction speed that best reflects performance during this type of task, we acquired measures of static and dynamic lower extremity strength for the ankle, knee, and hip joints.

METHODS

Participants

Fifty-six healthy, community-dwelling older adults (36 women and 20 men; mean ± standard deviation: age, 72 ± 5 years; height, 1.64 ± 0.09 meters; mass, 76.0 ± 14.0 kg) volunteered and were paid to participate in this study, which was part of a larger study of falling in these older adults (12). Prior to acceptance, the individuals were examined by a geriatrician for the presence of exclusionary factors that included neurological, musculoskeletal, cardiovascular, pulmonary, and other systemic disorders that would limit the individuals' ability to participate. In addition, bone mineral density of the right femoral neck, assessed by dual-energy x-ray absorptiometry (Hologic QDR 1000; Waltham, MA) required a minimum value of 0.65 $g \cdot cm^{-2}$ for acceptance into the study. All protocols were approved by the institutional review board, and all participants provided written informed consent.

Release From Forward Lean

The methods have been previously reported in detail (12). The ability to recover from a forward lean using a single step was evaluated as the maximum recoverable angle of lean. Participants were released without warning from a forward-leaning position by means of an electromagnetic support system. When remotely deactivated, the electromagnet removable core was immediately released thereby initiating a forward-directed fall. Participants were protected from falling to the ground by a full-body safety harness attached to a ceiling-mounted track by a pair of shock-absorbing dynamic ropes.

At the start of each trial, participants stood with their arms folded across the chest, feet approximately shoulder-width apart, and the heels aligned. The foot positions were marked on the floor to maintain consistency between trials. Participants leaned forward until restricted by the electromagnetic support system. They were asked to keep their body rigid and to maintain contact of the heels of the shoes with the ground. At some of the larger angles of lean, the heels were allowed to lift off of the ground slightly. During the initial positioning of the participant, the specific lean angle was measured using a goniometer as the angle between vertical and the line between the lateral malleolus and the greater trochanter.

After being correctly positioned, the participants were informed of the impending release. Participants were instructed that, after sensing the release, they were to take a single step to restore their balance. The stepping foot—that is, the one preferred for balance recovery—was determined before testing. Participants were instructed to maintain their arms folded across the chest and to keep some part of the nonstepping foot in its original position on the ground. A recovery that met these criteria was demonstrated to each participant by an investigator, but no instruction regarding recovery strategies was provided.

Participants performed two consecutive trials at each of 5, 10, 15, and 20 degrees of forward lean unless two failed recoveries occurred at a given angle of lean. A failed recovery resulted if, following the initial step, the arms were unfolded, the stepping foot moved entirely from the initial recovery step position, the entire nonstepping foot moved, or the body was completely supported by the harness system.

Joint kinematics were recorded using a six-camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA) operating at 60 Hz to track the motion of 14 hemispherical passive reflective markers placed on the head and bilaterally on the lower extremities and torso. Postprocessing analysis determined the maximum recoverable lean angle as the sagittal plane-included angle between the vertical and the axis from the lateral malleolus and the computed body center of mass averaged over 0.1 second prior to the instant of release.

Lower Extremity Strength

The methods have been previously reported in detail (13). The maximum force associated with voluntary isometric and isokinetic contractions (MVC) was measured for ankle plantarflexion and dorsiflexion, knee flexion and extension, and hip flexion and extension using a Kin-Com H-500 dynamometer (Chattanooga Corp., Chattanooga, TN). For the isometric contractions, a series of 3-second isometric MVCs was performed at a joint-specific, randomized set of joint angles. Two trials of isokinetic strength were measured concentrically at 30°/s and 90°/s and eccentrically at 30°/s for each joint motion. Participants were instructed to push or pull ''as hard and fast as you can'' at the start of and throughout each MVC. During the protocol, the arms were kept folded across the chest. Measures of ankle and hip strength were acquired with the participants in a supine position. Measures of knee strength were acquired with the participants in a seated position. Isometric, concentric, and eccentric exertions were tested in this order. Orders of the isometric joint angles were randomized.

Postprocessing of the dynamometer data used a participant-specific, validated, mathematical model to compensate for artifacts introduced by gravity, system accelerations and compliances, distal limb segment motion, and off-axis force components (13). Maximum isometric and isokinetic strengths were extracted from standardized joint- and direction-specific moment relationships derived using polynomial functions. As an index of muscle power, the maximum rate of moment increase was determined across all exertions in a given direction. Strength (moment) measures were expressed as a percentage of body weight × body height in accordance with the results of an allometric scaling procedure (14).

Statistical Analysis

The initial statistical approach was performed on a subset of the participants from the lowest and highest quartiles based on the maximum recoverable lean angle. A series of independent *t* tests was used to determine the strength and power measures for which the between-group differences were significant. These strength measures were then entered into a stepwise discriminant analysis, the purpose of which was to determine the extent to which the variable set could correctly classify the subsets of participants. Lastly, the variables selected by the discriminant analysis procedure as significant predictors of group membership, i.e., quartile, were used in a stepwise multiple regression procedure conducted using the data from all of the participants in the sample ($n = 56$). The purpose of the regression procedure was to determine the extent to which the maximum recoverable lean angle could be predicted using the variables identified in the discriminant analysis procedure. All statistics were performed using SPSS version 12.0 (Chicago, IL).

Results

The difference between the maximum recoverable lean angle of those participants at or below the 25th percentile (11 ± 2°; $n = 14$) and those participants at or above the 75th percentile (20 ± 3°; $n = 14$) was significant ($p < .001$). The lowest and highest quartiles were 36% and 57% male, respectively. A binomial test procedure revealed that the observed distribution of men and women in both subsets was not significantly different than 50%.

Based on the results of the series of independent *t* tests comparing the highest and lowest quartiles, 17 variables qualified for entry in the stepwise discriminant analysis (Table 1). The stepwise discriminant analysis subsequently reduced this set of variables to a single variable, the normalized maximum isokinetic dorsiflexion strength at 90°/s (Wilks'

Table 1. Descriptive Statistics of the Variables for Which Significant Differences Were Found Between Participants in the Lowest and Highest Quartiles of Maximum Recoverable Lean Angle

Variable*	Lowest Quartile, Mean ± *SD*	Highest Quartile, Mean ± *SD*
Isometric plantarflexion	5.94 ± 1.60	8.06 ± 2.09
Isometric dorsiflexion	2.04 ± 0.40	2.51 ± 0.47
Isokinetic plantarflexion		
30°/s	3.05 ± 1.32	4.83 ± 1.52
90°/s	1.68 ± 0.78	3.14 ± 1.29
Eccentric	4.90 ± 1.35	6.46 ± 1.73
Isokinetic dorsiflexion		
30°/s	1.28 ± 0.28	1.67 ± 0.35
90°/s	0.70 ± 0.16	1.10 ± 0.28
Plantarflexion (rate of moment generation)	2.25 ± 0.59	3.00 ± 0.64
Isometric knee extension	11.25 ± 2.04	13.67 ± 2.88
Isometric knee flexion	5.13 ± 1.08	6.38 ± 1.80
Isokinetic knee flexion		
30°/s	3.21 ± 1.04	4.23 ± 1.35
90°/s	2.79 ± 1.08	3.84 ± 1.18
Eccentric	4.56 ± 1.03	5.82 ± 1.85
Isometric hip flexion	9.05 ± 1.64	11.30 ± 2.25
Isokinetic hip flexion		
30°/s	5.51 ± 1.34	6.79 ± 1.45
90°/s	3.76 ± 1.70	5.75 ± 1.42
Hip extension (rate of moment generation)	2.35 ± 0.57	2.81 ± 0.57

Notes: * Strength and rate of moment generation variables are expressed as a percentage of body weight × body height and body weight × body height/second, respectively.

SD = standard deviation.

lambda = 0.574, $p = .002$). The discriminant function correctly classified 82.1% of the participants.

In the highest and in the lowest quartiles, the sex-related differences for normalized maximum isokinetic dorsiflexion strength at 90°/s were not significant. The isokinetic dorsiflexion strength at 90°/s for the men was 0.23% and 0.21% body weight × body height smaller than that of the women for the lowest and highest quartile, respectively ($p = .62$ and 0.78, respectively).

In contrast to the between-sex comparisons in the highest and lowest quartiles of maximum recoverable lean angle, across the entire participant pool the strength and power of the older men was generally larger than that of the older women ($p = .002$ and .003, respectively) as indicated by multivariate analysis of variance. Parenthetically, an a posteriori discriminant analysis correctly classified 86% of all of the older adults (14 of 20 men and 34 of 36 women) based on maximum eccentric knee flexion, maximum eccentric plantarflexion, and maximum eccentric hip flexion strength (Wilks' lambda = 0.44; $p < .001$).

Despite their generally greater lower extremity strength and power, men did not have a significantly larger maximum recoverable lean angle than women. The maximum recoverable lean angle for the men ($n = 20$) was 16.2 ± 4.7° and that of the women ($n = 36$) was 14.9 ± 3.0° ($p = .197$).

The stepwise multiple regression procedure applied to the entire sample of older adults revealed a quadratic relationship between maximum recoverable lean angle and maximum isokinetic dorsiflexion strength at 90°/s. The resulting equation (Figure 1) was significant ($p < .001$) and accounted for 29.5% of the shared variation.

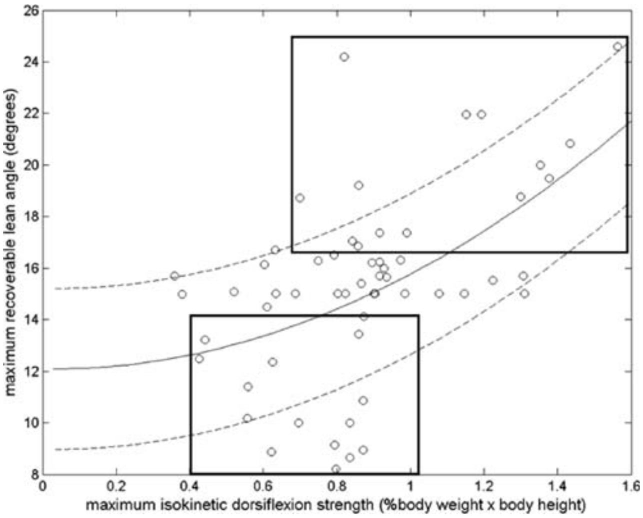

Figure 1. Scatterplot of individual data ($n = 56$) for maximum isokinetic dorsiflexion strength at 90°/s and maximum recoverable lean angle. The regression equation [maximum recoverable lean angle = 12.091 + (0.389 × maximum isokinetic dorsiflexion strength^2)] is plotted as the solid line. Plus and minus the standard error ($SE = 3.12$) are plotted as the dashed lines. The boxes denote those participants initially stratified into the lowest and highest quartiles based on maximum recoverable lean angle.

Discussion

The present study was undertaken to determine the extent to which measures of lower extremity strength and power contribute to the maximum recoverable lean angle in healthy, community-dwelling older men and women. The results revealed that isokinetic dorsiflexion strength was a significant contributor to the maximum recoverable lean angle of these older adults. However, about 70% of the variance of maximum recoverable lean angle remained unaccounted for by lower extremity strength. In light of the importance of lower extremity speed to performance of this task (3,7,8) and the importance of arresting the angular momentum of the body after recovery foot placement, the emergence of maximum isometric dorsiflexion strength as the single most important predictor of performance was not expected. However, the required lower extremity speed and the trajectory of the foot during the task, particularly the height of the foot above the ground (15), does provide some support for the role of ankle dorsiflexion in contributing to adequate ground clearance of the foot.

In contrast to previous work (8), the older men in the present study were unable to translate the advantage of generally greater lower extremity strength to a larger maximum recoverable lean angle. In the previous study, the maximum recoverable lean angle of older men was significantly larger, by about 47%, than that of older women (8). Indeed, the maximum recoverable lean angle of the men in that study was about 48% larger than that of the men in our study. The maximum recoverable lean angle of the women in that study was about 9% larger than that of the women in our study. The cause(s) of such between-study disparity of the results for the men is not immediately evident. The protocols used appear to be quite similar as were the methods used to select participants. In the studies by Wojcik and colleagues (3,8), the maximum recoverable lean angle of older men ($n = 10$) and older women ($n = 5$) was 24 ± 4° and 16 ± 5°, respectively. We noted that these values are similar to those of the older men and women in our study who placed in the highest sex-based quartile. For those older men ($n = 5$) and women ($n = 12$), the maximum recoverable lean angle was $22 \pm 2°$ and $18 \pm 2°$, respectively ($p = < .001$). Therefore, it is possible that a sampling issue contributed to the between-study differences.

The finding of a relationship between dorsiflexion strength and maximum recoverable lean angle, although unexpected, is consistent with a body of literature that has linked dorsiflexion strength to falls in older adults. Dorsiflexion strength has retrospectively (e.g., 16,17) and prospectively (e.g., 18,19) discriminated older adults who fell from those who did not fall during a 1-year period. The mechanisms by which lower dorsiflexion strength contributes to falls have not been defined. However, significant differences in dorsiflexion kinematics and kinetics at the beginning of swing phase of gait for older adults who fall and those who do not fall have been reported (20,21). In particular, older adults who fell during the 1-year follow-up period demonstrated decreased dorsiflexion range of motion and a delay in the onset of dorsiflexion, both of which were associated with an insufficient ground clearance during the swing phase (21). Although locomotion is not generally thought of as requiring substantial levels of available muscle strength, the possible relationship between muscle strength and ground clearance variables suggested by the extant literature may be of interest to investigate further.

The fact that about 70% of the variance in maximum recoverable lean angle was not accounted for by lower extremity strength suggests the contributions to performance of other, possible nonstrength-related variables. One such variable for a task such as the one used in this experiment may be lower extremity coordination (22). That is, the ability not only to create requisite joint moments but also to do so in an appropriate temporal framework. In that study, it was shown that maximum knee-extension strength and a measure of the coordination of the knee and hip joint were independent and statistically significant predictors of maximum vertical jump height in young adults. Indeed, the standardized regression coefficients of strength and coordination were similar, indicating for example that the advantage conferred by knee-extension strength on maximum vertical jump height performance may be undermined by poor coordination (and vice versa). In the context of the task used in the present study, lower extremity strength plays an essential role in generating rapid limb motion and arresting the angular momentum of the body acquired after the release. However, the relatively low proportion of variance of maximum recoverable lean angle accounted for by lower extremity strength suggests substantial contributions to successful performance of this task by other performance variables.

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