Stepping Performance During Obstacle Clearance in Women: Age Differences and the Association with Lower Extremity Strength in Older Women

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OBJECTIVE: To compare stepping performance during obstacle clearance in younger and older women, and to examine the relationship between lower extremity strength and stepping performance during obstacle clearance in older women.

DESIGN: Correlational study.

SETTING: A small community.

PARTICIPANTS: Twenty-four older women (mean age = 74.4), and 16 younger women (mean age = 20.7). The older participants lived independently in the community and were able to walk unaided.

MEASUREMENTS: Lower extremity muscle strength, measures of stepping performance including reaction time, movement time, extent of obstacle clearance, time to clear obstacle, among others.

MAIN RESULTS: The older women were far slower in stepping than the younger women. Toe trajectories differed between older and younger women during the initial portion of the step. The younger women tended to lift the toe straight up, whereas the older women tended to move the toe backward, away from the obstacle, passing farther from the obstacle when the toe cleared the obstacle height. There was little, if any, association between relative lower extremity strength and stepping performance during obstacle clearance in older women.

CONCLUSIONS: Dramatic differences in the speed of volitional stepping performance were found between younger and older women. Among the older women, lower extremity strength was not related to volitional stepping performance. J Am Geriatr Soc 48:1414–1423, 2000.

Key words: strength; older people; stepping; mobility

The well-documented reduction in muscle strength with advancing age[1,2] has been implicated as a cause of increased susceptibility to stability problems such as falls.[1–7] However, the specific ways in which strength declines influence fall risk in older adults have not been thoroughly explored. One possibility is that decreased lower extremity strength affects the abilities of some older adults to safely step over obstacles.[8]

Obstacles at fixed locations in the gait path are usually avoided by viewing them, identifying the obstacle's location and characteristics, and adjusting one's gait to go around or step over the obstacle.[9] When gait adjustments are absent or ineffective, the foot can strike the obstacle during the swing phase of gait, causing a trip. Trips are one of the most prevalent causes of falls,[10,11] and the swing phase of gait is a fundamental movement pattern in the avoidance of or recovery from a trip. An increased risk of obstacle contact with age has been observed in healthy persons.[12] Stepping over an obstacle requires greater muscle force than does common walking,[8] and this increased demand may affect the abilities of older adults with decreased lower extremity strength to safely step over obstacles.

Because of the prevalence of tripping as a cause of falls, we chose to examine stepping performance during obstacle clearance in younger and older women, with the prospect of identifying movement properties exhibited by older adults that could place them at risk for falls (e.g., extreme slowness of movement). Moreover, because of the possibility that lower extremity strength influences the ability to safely step over obstacles, we examined the relationship between lower extremity strength and stepping performance during obstacle clearance in older women. We expected to find that younger women would be better (e.g., faster) than the older women at executing the step, and that among the older women, strength would be related to stepping performance.

METHODS

Participants

The participants for this study were 16 younger women (mean age = 20.7, standard deviation (SD) = 1.0, range = 19–22) and 24 older women (mean age = 74.4, SD = 3.4, range = 69–81). To qualify for participation, the older volunteers had to live independently in the community and be able to walk unaided. Participants were also screened for serious medical or mobility problems. Fall history data was collected to estimate how representative the sample of older

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women was in terms of the frequency of falls. Eleven of the 24 older participants recalled falling at least once in the previous 12 months, and four persons recalled falling three or more times. The fall rate of 46% is within the range of the 30–50% typically reported for representative samples of community-dwelling older adults.[13–15] All participants indicated that they engaged in some sort of physical activity. Among the older women, the most common activities were walking and yard work/gardening. The most common activities among the younger women were walking, weight training, biking, and running.

Procedure

Step Test

Each participant was tested on the speed with which she could step over an obstacle positioned 3 cm in front of her left foot. Participants wore their own tennis/running/walking shoes. The obstacle was a block of rigid Styrofoam, 8 cm tall × 30 cm wide × 10 cm deep. Participants stood with their feet shoulder-width apart, with the right foot one-half foot length ahead of the left. Participants were instructed to stand motionless and wait for a light stimulus positioned 1.5 m in front of them at 60% of eye height to activate. Upon detection of the light, individuals were to step over the obstacle as quickly as possible without striking it. The right (support) foot was to remain in its original position. Participants were asked to maintain a stable posture for 5 seconds after completing the step as an indication that the step was functional in that it did not result in a fall. Participants received three practice trials and five actual trials, with 30 seconds rest between trials. Trials were repeated if the participant anticipated the stimulus or struck the obstacle.

Because the step was begun intentionally at the presentation of a visual stimulus, it was classified as a volitional step. Volitional steps differ from compensatory steps, which result from a destabilizing event such as a trip and are somewhat reactive. In experiments, volitional stepping is typically elicited by visual or auditory cues, and has a weaker intrinsic relationship to recovery from a trip than do compensatory responses. However, the volitional stepping task used in this study required movements extremely similar to those found in obstacle clearance during locomotion, including the swing leg movement before and following a trip. Moreover, tripping over a known obstacle while initiating locomotion (i.e., tripping during a volition step) can and does happen. Therefore, the volitional step was considered appropriate for this exploratory assessment of the association between strength and stepping performance.

Reaction time (RT) and movement time (MT) were recorded using switches incorporated in the floor. Each participant was recorded on videotape using a 60-Hz Panasonic WV-D5100HS camera (Camera 1) and a 60 Hz Panasonic AG-455P camera (Camera 2). The cameras were synchronized using a secondary light visible in both cameras that was activated simultaneously with the primary visual stimulus. Camera 1 recorded the entire left side of the body, and Camera 2 recorded the left foot and obstacle only. Videotapes of the trials in which participants recorded their three fastest MTs were selected for digitizing, for which a video motion measurement system from Peak Performance Technologies, Inc. (Denver, CO) was used. To automate digitizing, reflective markers were placed at the left shoulder, hip, knee, and ankle joints, as well as the distal end of the fifth metatarsal of the left foot. Digitizing began at the first frame in which the light stimulus was visible and continued for 2 seconds (120 frames). Frames containing toeoff (i.e., the first frame in which the foot was not in contact with the ground) and footstrike (i.e., the first frame in which the foot made contact with the ground) were identified. Videotape from Camera 2 was digitized manually using the forward-most point on the shoe (i.e., toe), the rear-most point on the shoe's sole (i.e., heel), and the top left and right corners of the obstacle as landmarks. Manual digitizing began at the first frame in which the synchronizing light was visible and continued for 2 seconds (120 frames). The frame containing toeoff was identified.

The kinematic variables computed and averaged across each participant's three trials included: (a) linear displacement, velocity, and acceleration of the shoulder, hip, knee, ankle, foot, and toe; (b) angular displacement, velocity, and acceleration of the ankle, knee, hip, and trunk; and (c) several spatial and temporal measures of obstacle clearance by the toe. Ankle, knee, and hip angles were computed as absolute angles, whereas the trunk angle was computed as a relative angle (i.e., trunk position relative to the vertical). Measures of obstacle clearance included (a) the horizontal distance between the toe and the obstacle at the point the toe cleared the obstacle height, (b) the vertical distance between the toe and the obstacle when the toe crossed the plane of the near vertical surface of the obstacle, and (c) the time for the toe to clear the obstacle height.

Strength Tests

The older participants were tested for lower extremity strength, whereas the younger women were not. The purpose of testing the younger women on the same stepping task as the older women was to inform our decision making about the kinematic variables to include in a correlational analysis of the relationship between strength and stepping performance in older women. Variables in which the older women were dramatically inferior to the younger women were good candidates for the analysis, assuming there was a reason to believe that the parameter was also important to safe stepping performance. The muscle groups chosen for testing represent the primary movers/stabilizers of the lower extremities. Strength tests for the older women consisted of hip flexion and extension, knee flexion and extension, and ankle plantar flexion and dorsiflexion. With the exception of plantar flexion, the apparatus used to test strength was a computerized cable tensiometer which utilized LabVIEW software (National Instruments, Austin, TX) to measure peak force in kilograms.

Strength testing began by having participants take the position appropriate for a given test on a sturdy table that had a padded nonskid surface. Once in position, the left leg/foot was connected to the tensiometer, which permitted a maximum of 30 cm of linear displacement (e.g., approximately 45° of angular displacement at knee). Increased displacement resulted in greater resistance. The initial joint angle for a given test was held constant across participants. Participants were instructed on the procedure for a given test and its goal, which was to exert as much force as possible (i.e., move the limb through as large a range of motion as possible). Two practice trials were performed and three official trials followed, with maximum peak force recorded for each. There was 30 seconds rest between trials and 5 minutes rest between strength tests. The cable tensiometer was not used for the plantar flexion test, rather, participants performed a modified standing single-leg heel-rise test.

The reliability of the strength tests had been determined previously using 24 men and women between the ages of 65 and 84 years. Using intraclass correlations computed from two separate tests of strength, the coefficients for hip flexion and extension, knee flexion and extension, and ankle plantar flexion and dorsiflexion strength were $r = 0.96$, $r = 0.90$, $r = 0.99$, $r = 0.94$, $r = 0.84$, and $r = 0.83$, respectively.

Data Analysis

To ascertain whether there were differences in stepping performance between the younger and older women, t tests were performed on indicators of stepping performance. To determine the relationship between strength and stepping performance in older women, relative lower extremity strength (peak force in kg/body weight in kg) was correlated with stepping performance using Pearson r. Given the small sample size of 24, Spearman rank-difference correlations were also computed. There were no differences in the results of the analyses and, therefore, Pearson r is reported.

RESULTS

Age Differences in Stepping Performance During Obstacle Clearance

Age differences in stepping performance during obstacle clearance are reported in Table 1.

Response Time

The older women were 0.331 second (26%) slower than the younger women in stepping over the obstacle. MT accounted for a much larger proportion of the difference in response time than did RT.

Linear Displacement

Movement trajectories at the left shoulder, hip, knee, and ankle joints, as well as the distal end of the fifth metatarsal of the left foot are displayed in Figure 1. With the exception of the older womens' 0.05 m greater horizontal displacement of the shoulder, the older and younger women exhibited similar linear movement displacements.

Obstacle Clearance

In just seven trials (four for older women and three for younger women) was the obstacle struck during the step. Thus, obstacle clearance was characterized in terms of (a) the horizontal distance between the toe and the obstacle at the point the toe cleared the obstacle height, (b) the vertical distance between the toe and the obstacle when the toe crossed the plane of the near vertical surface of the obstacle, and (c) the time for the toe to clear the obstacle height. Older and younger women differed significantly on the first and latter variables. A comparison of the toe trajectories during the step is illustrated in Figure 2. The younger women tended to lift the toe straight up, whereas the older women tended to move the toe backward, away from the obstacle, passing 0.02 m (59%) farther from the obstacle when the toe cleared the obstacle height. Furthermore, the older women took 0.086 second (37%) longer to clear the obstacle height with the toe than the younger women, as timed from first observable ankle movement.

Among the older women there was a significant correlation between the horizontal clearance distance of the toe when it cleared the obstacle height and overall response time, $r = 0.41$ ($n = 24$, $P < .05$). In a manner of speaking, there appeared to be a trade-off between the risk of striking the obstacle and step response time. The relationship was not present, however, until after the toe had cleared the obstacle height. Consequently, increased horizontal clearance distance did not result in greater obstacle clearance time.

Linear Velocity and Acceleration of the Foot

The older women exhibited inferiority in the maximum velocity of the foot during the step (see Table 1). Also, the older women took 40% and 26% longer to reach their maximum vertical (upward) and horizontal velocities, respectively, as timed from the first observable ankle movement.

Angular Displacement

With two exceptions, the older and younger women exhibited similar angular displacements. As shown in Table 1, the older women exhibited significantly greater plantar flexion following toeoff than the younger women did, 9.1° and 5.0°, respectively. Also, close inspection of the trunk data displayed in Figure 3 revealed that both groups tended to lean backward slightly at step initiation, after which the younger women quickly leaned forward past vertical. The older group's forward lean was delayed and of much smaller magnitude.

Angular Velocity and Acceleration

The older women exhibited inferiority in maximum angular velocity and acceleration during the step (Table 1). The largest difference was observed in maximum angular acceleration of knee flexion, where the older women were 47% slower than the younger women.

Coordination

The coordination of stepping was analyzed by examining joint coupling via angle-angle diagrams. Evaluation of knee-ankle, hip-knee, and trunk-hip angle-angle diagrams indicated that coordination dynamics in terms of joint coupling were similar for the older and younger women. As an example, the hip-knee diagram is presented in Figure 4.

The Association Between Relative Lower Extremity Strength and Stepping Performance During Obstacle Clearance in Older Women

Results of the strength measurements for the older women are presented in Table 2. Mean relative strength values ranged from a low of 0.3 for dorsiflexion, to a high of 0.73 for hip extension. There was considerable variability in relative lower extremity strength among the participants. In every test, the strongest participant was at least twice as strong, and as much as five times stronger than the weakest participant.

From the kinematic variables included in Table 1, those that were perceived as having a possible affect on the success with which older women stepped over the obstacle were correlated with measures of relative lower extremity strength. First, variables were chosen based on previous research. For example, poor ankle dorsiflexion strength has been shown to be associated with increased fall risk.[3–6] Therefore, it was

Table 1. Age Differences in Stepping Performance During Obstacle Clearance in Women

	Younger Women (n = 16) Mean ± SD	Older Women (n = 24) Mean ± SD	Percentage Difference for Older Women
Stepping time			
Reaction time (RT) (seconds)[¶,‖]	0.553 ± 0.035	0.678 ± 0.067	+18%
Movement time (MT) (seconds)[¶,#]	0.405 ± 0.058	0.600 ± 0.10	+32%
Response time (seconds)[¶,††]	0.958 ± 0.062	1.289 ± 0.146	+26%
Linear displacement			
Horizontal shoulder displacement (m)[†]	0.228 ± 0.056	0.274 ± 0.074	+17%
Horizontal hip displacement (m)	0.243 ± 0.04	0.245 ± 0.047	0%
Vertical foot displacement (m)	0.263 ± 0.042	0.252 ± 0.066	−4%
Step length (m)	0.484 ± 0.038	0.474 ± 0.049	−2%
Obstacle clearance			
Horizontal distance between the toe and the obstacle when the toe cleared the obstacle height (m)[‡]	0.034 ± 0.02	0.054 ± 0.023	+37%
Vertical distance between the toe and the obstacle when the toe crossed the plane of the near vertical surface of the obstacle (m)	0.111 ± 0.063	0.138 ± 0.059	+20%
MT to clear obstacle height with the toe (seconds)[¶,‡‡]	0.146 ± 0.02	0.232 ± 0.038	+37%
Linear velocity and acceleration of the foot			
Maximum horizontal velocity of the foot (forward) (m/second)[¶]	2.67 ± 0.40	1.90 ± 0.49	−29%
Maximum vertical velocity of the foot (upward) (m/second)[§]	2.21 ± 0.418	1.57 ± 0.56	−29%
Maximum vertical velocity of the foot (downward) (m/second)[¶]	1.77 ± 0.36	1.16 ± 0.40	−34%
MT to maximum horizontal velocity of the foot (forward) (seconds)[¶,‡‡]	0.305 ± 0.039	0.426 ± 0.082	+40%
MT to maximum vertical velocity of the foot (upward) (seconds)[¶,‡‡]	0.162 ± 0.023	0.219 ± 0.04	+26%
Maximum horizontal acceleration of the foot (forward) (m/seconds^2)[¶]	24.6 ± 5.0	17.1 ± 4.1	−30%
Maximum vertical acceleration of the foot (upward) (m/seconds$^{22)}$[¶]	25.5 ± 7.2	14.6 ± 7.4	−43%
Maximum vertical acceleration of the foot (downward) (m/seconds^2)[§]	16.7 ± 6.5	9.3 ± 4.6	−44%
Angular displacement			
Angular displacement of the trunk (degrees)	8.1 ± 3.0	9.5 ± 5.0	+15%
Angular displacement of hip flexion (degrees)	57.6 ± 5.6	58.9 ± 8.4	+2%
Angular displacement of knee flexion (degrees)	94.1 ± 8.2	86.9 ± 13.9	−8%
Angular displacement of ankle dorsiflexion following toeoff (degrees)	5.7 ± 3.2	6.9 ± 4.7	+21%
Angular displacement of ankle plantar flexion following toeoff (degrees)[†]	5.0 ± 3.9	9.1 ± 6.2	+82%
Angular velocity and acceleration			
Maximum hip flexion velocity (degrees/second)[¶]	296.2 ± 42.3	214.4 ± 47.9	−28%
Maximum hip extension velocity (degrees/second)[¶]	232.5 ± 50.7	161.3 ± 47.8	−31%
Maximum knee flexion velocity (degrees/second)[¶]	570.4 ± 89.6	399.3 ± 111.9	−30%
Maximum knee extension velocity (degrees/second)[¶]	482.6 ± 79.8	341.7 ± 91.5	−29%
Maximum ankle dorsiflexion velocity following toeoff (degrees/second)	68.4 ± 32.9	68.2 ± 43.6	0%
MT to maximum hip flexion velocity (seconds)[§§]	0.148 ± 0.064	0.182 ± 0.064	+19%
MT to maximum knee flexion velocity (seconds)[†,§§]	0.157 ± 0.147	0.193 ± 0.051	+19%
Maximum acceleration of hip flexion (m/second^2)[¶]	2527 ± 635	1451 ± 570	−43%
Maximum acceleration of knee flexion (m/second^2)[¶]	4783 ± 1630	2527 ± 1215	−47%

*The italicized variables were chosen for the exploratory correlation analysis of relative lower extremity strength and stepping performance during obstacle clearance in older women.

†$P < .05$.

‡$P < .01$.

§$P < .001$.

¶$P < .0001$.

‖Time was calculated from the activation of the visual stimulus to removal of the foot from the switch upon which participants were standing.

#Time was calculated from the removal of the foot from the switch upon which participants were standing to contact with the pressure mat beyond the obstacle.

††Time was calculated by summing RT and MT.

‡‡Time was calculated beginning with the first observable movement of the ankle.

§§Time was calculated beginning with the first observable angular movement of the specified joint.

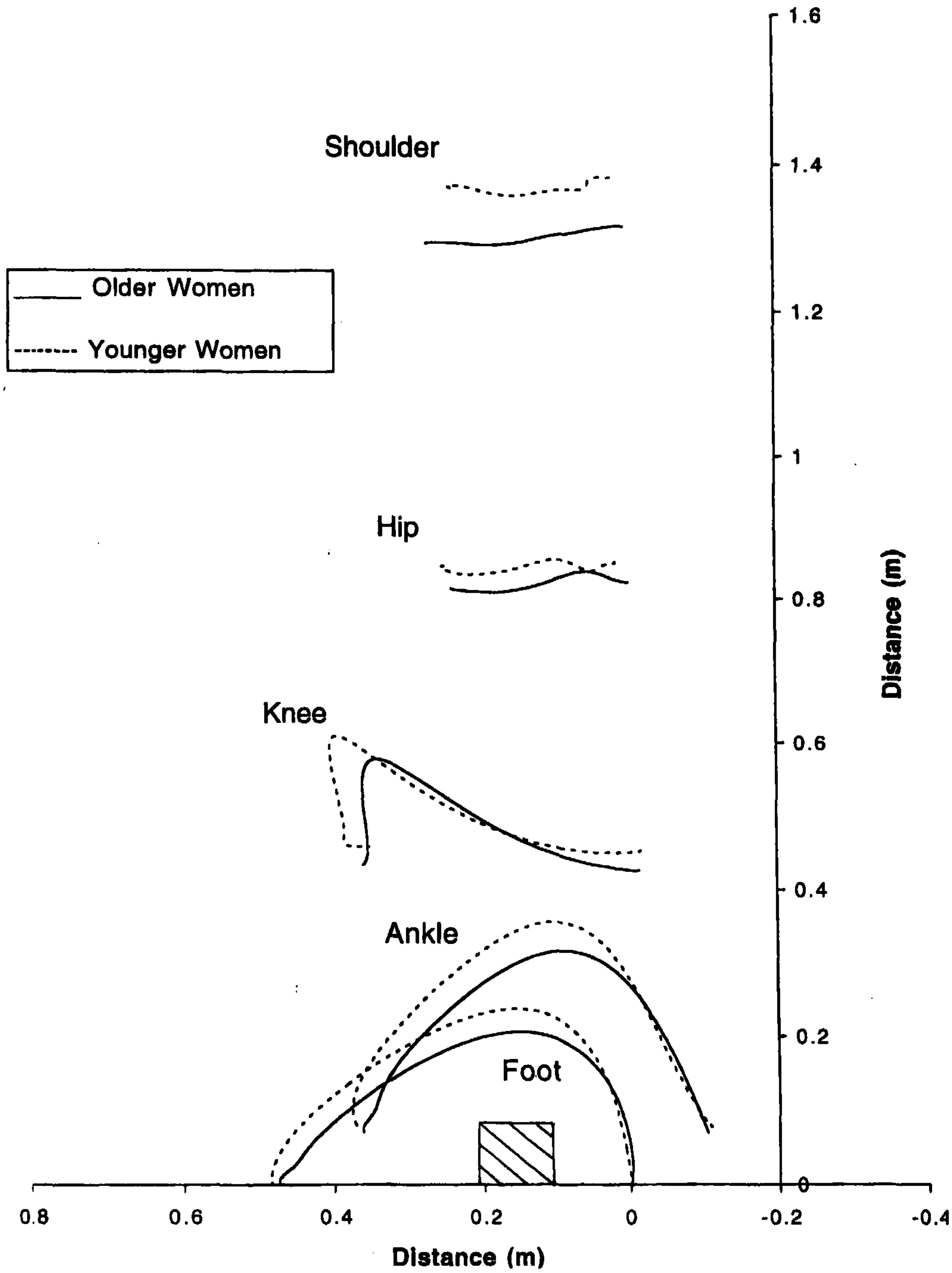

Figure 1. Movement trajectories of the left shoulder, hip, knee, ankle, and foot (distal end of fifth metatarsal) during stepping and obstacle clearance for older and younger women.

logical to assess the relationship between dorsiflexion strength and the extent and velocity of dorsiflexion following toeoff in the step. Second, variables in which the older women were dramatically inferior to the younger women were good candidates for the analysis, when there was also a logical reason to believe that the variable was important to safe stepping performance. The variables chosen for the analysis are indicated in Table 1.

The results of this exploratory correlational analysis revealed a nearly complete lack of association between relative lower extremity strength and stepping performance during obstacle clearance in older women. Of the 28 indicators of stepping performance included in the analysis, not a single one was related significantly to total relative lower extremity strength, a sum of five of the individual strength measures (i.e., no coefficient exceeded $r = 0.32$, $P = .13$). Nonetheless, the direction of the relationships were consistent with expectations. For example, the coefficients for total relative lower extremity strength and RT, MT, and MT to obstacle clearance were each negative ($r = -0.32$, $r = -0.12$, $r = -0.29$, respectively), as expected. In other words, there was a slight tendency for stronger participants to both react and move faster than weaker participants. Among the specific strength measures, there were just three significant correlations. First,

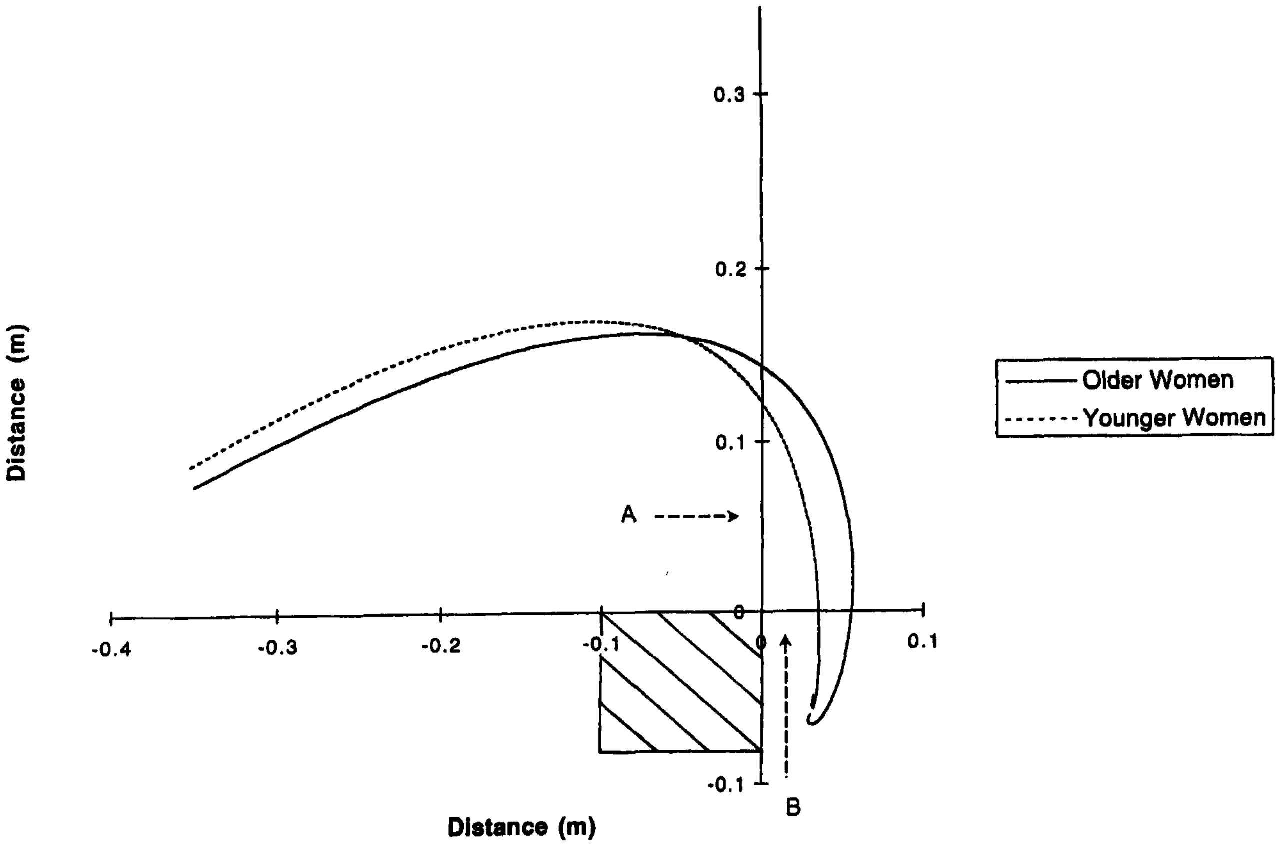

Figure 2. Movement trajectories of the toe during stepping and obstacle clearance for older and younger women. (*A* = the vertical distance between the toe and the obstacle when the toe crossed the plane of the near vertical surface of the obstacle; B = the horizontal distance between the toe and the obstacle at the point the toe cleared the obstacle height).

the correlation coefficient between relative dorsiflexion strength and MT to clear the obstacle height with the toe was $r = -0.57$ (n = 24, $P < .01$), indicating that participants with greater relative dorsiflexion strength tended to clear the obstacle height more quickly than those with poorer dorsiflexion strength. Second, relative knee flexion and extension strength were significantly correlated with the time to maximum vertical velocity of the foot in the upward direction, $r = -0.42$ (n = 24, $P < .05$) and $r = -0.45$ (n = 24, $P < .05$), respectively. That is, participants with greater relative knee strength tended to achieve maximum vertical velocity of the foot more quickly than participants with poorer knee strength.

DISCUSSION

Response Time

The fact that the older women were markedly slower in stepping over the obstacle than the younger women is not surprising. The slower RT observed in the older group of women is consistent with a previous report of slower RT in volitional forward stepping in older adults.[16] Response slowness in stepping is considered detrimental to functional performance, and fall avoidance in particular.[17]

Expressed as a proportion of response time, the deficit in MT for the older women was considerably larger than that of RT. This suggests that the origin of differences in stepping response time between the younger and older adults rests more in the decreased speeds with which older adults can move the lower extremities than in deficits in the sensory or cognitive processes involved in response initiation.[18] Slowness of movement among older adults could be the result of decreases in muscle strength.[19,20] Rapid stepping is characterized by a high velocity of movement,[21,22] and hip flexion and knee extension velocities largely determine the time required to position the recovery foot for ground contact, which often must occur within a limited time.[17] It has been suggested that muscle weakness could be influential by slowing the velocity of hip flexion and knee extension, as well as other joint movements.[23]

Muscle weakness could slow RT as well by increasing the time needed to achieve postural stabilization before step initiation. During normal quiet standing, the center of gravity is within the base of support and body weight is borne equally by the two legs. Before the initiation of forward stepping, body weight must be transferred to the support leg. An increase in vertical force from the stepping foot assists in this transfer by tilting the body such that the center of gravity moves over the support leg.[16] Increased weight transfer times have been observed in older persons, and have been partially explained by a lower peak vertical force from the stepping foot and a longer time to reach that force.[16] Of course, deficits in sensory (vision) or cognitive processing among the older women could also account for a portion of the difference in RT observed between the younger and older women.

Obstacle Clearance

Older women negotiated the obstacle differently than the younger women. As shown in Figure 2, the older women

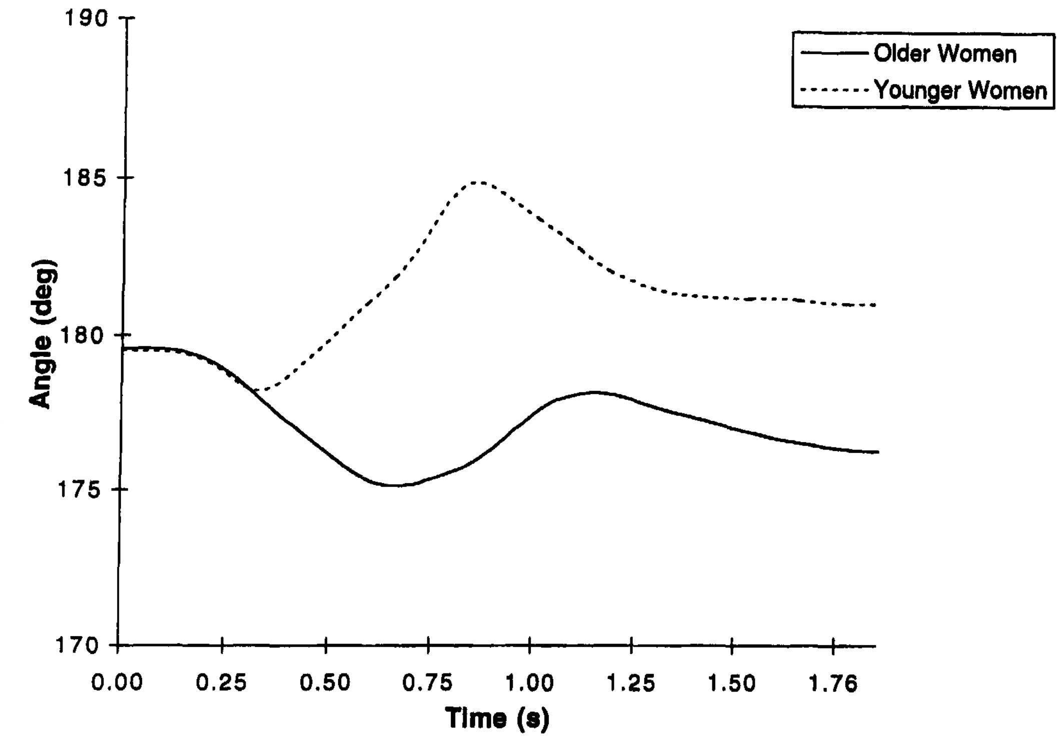

Figure 3. Angular trunk displacement during stepping and obstacle clearance for older and younger women. (Values less than 180° represent backward leaning, and values greater than 180° represent forward leaning).

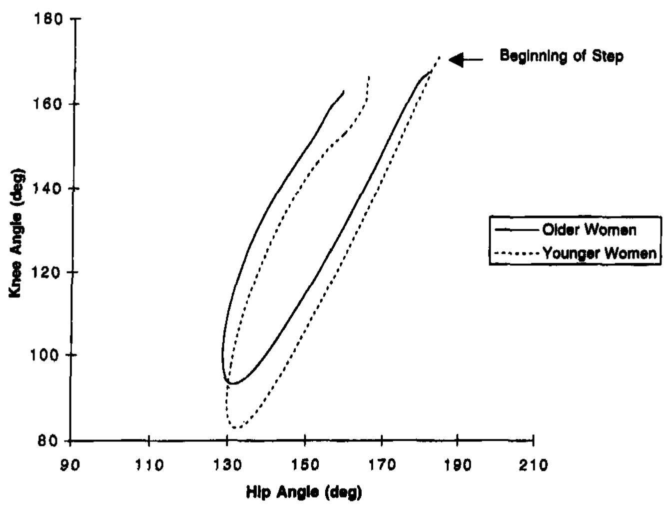

Figure 4. Angle-angle diagram of the hip and knee during stepping and obstacle clearance for older and younger women. (The difference in knee angle displacement was not statistically significant. See Table 1).

tended to begin the step by moving the toe backward, away from the obstacle, passing 0.02 m (59%) farther from the obstacle at the point the toe cleared the obstacle height than the younger women did. In contrast, the younger women tended to lift the toe straight up. The greater obstacle clearance among the older women presumably reflects a more cautious strategy,[24] and implies that the older women perceived the threat of the stepping task to be greater than the younger women did. Although the older women appeared to avoid the obstacle, which could be advantageous, they took 37% longer to clear the obstacle height with the toe than the younger women did. This deficit could be a disadvantage in terms of avoiding a trip or recovering from one.

Linear and Angular Displacement

Considering that the volitional stepping task in our study was constrained, the overall similarity in linear and angular displacement between the younger and older women is not surprising. For the same reason, it is not surprising that coordination in terms of joint coupling was similar as well (see Figure 4). However, in terms of angular motion, two interesting differences in displacement were observed. During the step, the younger women leaned forward more quickly and to a greater extent than the older women (see Figure 3). This could be the result of the superior stepping speed of the younger women. Any trunk flexion that occurs when stepping over an obstacle is partially a consequence of the reactive torque imposed by active hip flexion.[25] As shown in Table 1, the younger women had superior maximum angular velocity and acceleration of hip flexion, which likely contributed to the earlier onset and more extensive trunk flexion in the younger group.

Second, the older women exhibited nearly twice as much plantar flexion following toeoff as the younger women did. In fact, the older women allowed the toe to drop (relative to the ankle) an average of 6.4 cm, compared with 3.6 cm for the younger women. Excessive plantar flexion following toeoff could be disadvantageous by delaying the onset of knee extension and increasing the likelihood of obstacle contact via a delay in obstacle clearance. The timing and speed of knee extension is important because it is responsible for putting the swing leg in position to make contact with the support surface in time to retard the forward rotation of the body, and thus prevent a fall.

Table 2. Mean Relative Strength Values for Older Women

	Mean	Standard Deviation	Coefficient of Variation	Minimum	Maximum
a. Hip flexion (% body weight)	31.7	5.3	16.7	19.9	46.2
b. Hip extension (% body weight)	73.2	16.4	22.5	34.6	103.7
c. Knee flexion (% body weight)	31.1	6.2	20.0	20.9	48.0
d. Knee extension (% body weight)	49.0	13.1	26.7	20.7	78.9
e. Dorsiflexion (% body weight)	30.0	5.5	18.3	20.4	41.8
f. Plantar flexion (number of heel rises)*	20.3	8.0	39.7	7.0	39.0
Total strength (sum of a–e)	215.1	39.5	18.4	120	289

*For the plantar flexion test, participants performed a modified standing single-leg heel-rise test.

Poor ankle dorsiflexion strength[3–6] and plantar flexion strength[7,6] have been shown to be associated with increased fall risk. It is possible that the greater plantar flexion displacement following toeoff among the older participants results from a reduced ability to generate dorsiflexion torque, which would act to hold the toe up such that obstacle clearance occurs more quickly. Thelen et al.[26] observed that healthy older adults have marked declines, compared with young adults, in their ability to develop ankle joint torque rapidly. They suggested that the capacity of older adults to recover balance or to carry out other time-critical actions that require moderate to substantial strength may be degraded by these declines.

Before the initiation of volitional stepping, body weight has to be transferred to the supporting limb. An increase in vertical force produced by the stepping foot, which is applied partially via plantar flexion, assists in weight transfer by tilting the body such that the center of gravity moves over the supporting limb.[16] Longer weight transfer times have been observed in older adults,[16] and have been explained by the fact that older adults exhibit lower peak vertical force generated by the stepping foot, as well as a longer time to reach peak force. Thus, it is possible that the older women in the present study exhibited excessive planter flexion following toeoff because they needed more time to apply vertical force, and/or they needed to apply a relatively greater vertical force because of their longer step duration.

Even though both groups recorded nearly identical ankle dorsiflexion following toeoff, the older women recorded dramatically inferior (46%) maximum dorsiflexion velocity (see Table 1). We believe that lower dorsiflexion velocity could be disadvantageous by delaying the onset of knee extension and increasing the likelihood of obstacle contact via a delay in obstacle clearance.

Linear and Angular Velocity/Acceleration

In addition to superiority among the younger women in dorsiflexion velocity, the results of this study revealed the same trend for both linear and angular velocity and acceleration (see Table 1). Again, it has been suggested that age-related declines in peak muscle strength could contribute to the slowness of movement observed among older persons,[21,22] and that the demands of stepping over an obstacle may affect the abilities of older adults with decreased lower extremity strength to safely step over obstacles.[27]

The younger women were, on average, 8 cm taller than the older women. One could argue that the stepping task was more difficult for the older women because, relatively speaking, the obstacle was larger for them. The obstacle was 5% of the older group's mean stature, and 4.8% of the younger group's (a 4% difference). However, because leg length accounted for just 25% of the difference in stature (with the torso and head accounting for 75%), obstacle height relative to leg length was more similar (10.3% for the young women, and 10.6% for the older women (a 3% difference). It remains possible that a small portion of the inferior stepping performance of the older women could be attributed their shorter stature.

The Association Between Relative Lower Extremity Strength and Stepping Performance During Obstacle Clearance in Older Women

The results of this exploratory correlational study demonstrated that relative lower extremity strength was minimally related, if at all, to volitional stepping performance during obstacle clearance in older women. Even though the stepping task used in this study was not identical to stepping under many natural conditions, it was similar enough that this finding raises questions about the extent to which strength influences fall risk in situations demanding rapid swing leg movement, like the avoidance of or recovery from a trip. Stepping during obstacle clearance, even when rapid, does not appear to require maximum muscle forces. Therefore, moderate age-related reductions in strength may not be the limiting factor in generating movement speeds necessary for obstacle clearance.

Given the large number of correlations performed, the few significant correlations between relative strength and measures of stepping performance among the older women could simply have been regarded as chance occurrences. However, we believed cautious examination of the significant correlations was warranted. First, older women who possessed higher levels of relative dorsiflexion strength tended to take less MT to clear the obstacle height than weaker participants ($r = -0.57$, $n = 24$, $P < .01$). Shorter MT could be beneficial by making initial or repeat contact with obstacles less likely, and by allowing knee extension of the swing leg to commence sooner. Under the assumption that superior dorsiflexion strength could only produce shorter MT to obstacle clearance via an increase in the extent and/or rate of dorsiflexion at the beginning of the step, we examined the validity of this correlation. Close inspection of the data revealed that relative dorsiflexion strength was not even minimally related to the extent or velocity of dorsiflexion. That is, participants with higher relative dorsiflexion strength did not achieve shorter MTs to clear the obstacle height by moving the ankle joint through greater range of motion nor by moving it more quickly than weaker participants. Thus, the relationship between relative dorsiflexion strength and MT to clear the obstacle height should presumably be regarded as a chance occurrence.

Second, relative knee strength, both flexion and extension, were significantly correlated with MT to maximum vertical velocity of the foot in the upward direction, $r = -0.42$ ($n = 24$, $P < .05$) and $r = -0.45$ ($n = 24$, $P < .05$), respectively. That is, participants with greater relative knee strength tended to achieve maximum upward vertical velocity of the foot more quickly than participants with poorer knee strength. In particular, the relationship between MT to maximum vertical velocity and relative knee flexion strength could reflect functional importance, given that both reactive[25,28] and proactive strategies[29] during the task of stepping over obstacles employ knee flexion predominantly. Under the assumption that superior knee flexion strength could only produce shorter MT to maximum vertical velocity of the foot in the upward direction via an increase in the extent and/or rate of knee flexion during the step, we examined the validity of this correlation. Data analysis revealed positive but nonsignificant correlations between relative knee strength and the extent, velocity, and acceleration of knee flexion during the step ($r = 0.27$, $r = 0.31$, and $r = 0.26$, respectively). Although the data do not permit the declaration of causative attributes to knee flexion strength in the safety or effectiveness of stepping responses, the possibility remains that knee flexion strength may be mildly influential.

Limitations

Our study had several limitations. First, because we focused on women, the results cannot be generalized to men. Moreover, the older women who participated in this study were representative of a relatively healthy subgroup of older women. Even though there was considerable variability in relative lower extremity strength among the older participants, none of them would be considered frail. This is important because among stronger older adults, strength differences may yield little difference in performance, whereas among frail older adults, even minor strength differences might yield large performance differences.

Finally, as discussed earlier, it is possible that the volitional stepping response (elicited by visual cue) used in this study bears less resemblance to compensatory stepping elicited by foot contact with an obstruction than assumed. Stepping responses elicited by perturbations are executed more quickly than those elicited by visual cue.[22] Nevertheless, a single-leg compensatory stepping response seems to be extremely similar in temporal patterning to gait initiation (i.e., volitional stepping).[30–32] Compensatory and volitional stepping responses may arise from a basic motor program that acts as a common solution for both actions.[33] This might account for the similarity observed by McIlroy and Maki[23] in the patterning of the preparatory weight shift irrespective of the type of cue (visual or perturbational).

In conclusion, slowness of movement like that observed among the older women in this study is often attributed to decreases in lower extremity muscle strength with age. However, the results of this study leave little doubt about the lack of association between relative lower extremity strength and volitional stepping performance, including speed of movement, during obstacle clearance among healthy, community-dwelling older women. Further research will be required to determine the specific ways in which strength declines influence fall risk in older adults. Until the link between strength and fall risk can be more thoroughly explained, caution should be exercised when discussing resistance training as a way for older adults to reduce the incidence of falls, because it is unclear if and how it produces a preventative or restorative effect. Recommendations for future research include examining the relationship between strength and stepping performance in frail older adults, and using a more realistic stepping task. Moreover, given suggestions that the rate of force development may be a more important determinant than absolute peak force in time-critical tasks such as recovering from a trip,[34,35] it may be fruitful to closely examine this variable and its relationship to stepping performance.

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