Departures From Linearity in the Relationship Between Measures of Muscular Strength and Physical Performance of the Lower Extremities: The Women's Health and Aging Study

Luigi Ferrucci,[1,2] Jack M. Guralnik,[2] David Buchner,[3] Judith Kasper,[4]
Sarah E. Lamb,[3] Eleanor M. Simonsick,[2] M. Chiara Corti,[2] Karen Bandeen-Roche,[5]
and Linda P. Fried[6] for the WHAS Research Group

[1]Geriatric Department, "I Fraticini," National Research Institute (INRCA), Florence, Italy.
[2]Epidemiology, Demography, and Biometry Program, National Institute on Aging, Bethesda, Maryland.
[3]Department of Health Services, University of Washington, Seattle.
Departments of [4]Health Policy and Management and [5]Biostatistics,
The Johns Hopkins School of Hygiene and Public Health, Baltimore.
[6]Department of Medicine and Epidemiology, School of Medicine, Johns Hopkins Medical Institutions, Baltimore.

Background. Sarcopenia, an age-related reduction in muscular mass and strength, may cause a decline in physical functioning and subsequent loss of autonomy. It has been suggested that strength is associated with lower extremity function mainly in the lower portion of the range of strength. Identifying the threshold under which strength is most critical to function may help in targeting groups who may benefit most from exercise interventions.

Methods. The study uses data from the Women's Health and Aging Study. The study population, recruited by screening a population-based sample aged 65 years and older, comprised 1,002 women who represent the one-third most disabled women without severe cognitive impairment living in the community. Knee extensor and hip flexor strength were assessed using a hand-held dynamometer. Lower extremity performance was evaluated using tests of walking, standing balance, and rising from a chair.

Results. Among women tested for strength ($n = 892$), those who could walk (97%), do the side-by-side stand (87%), or complete 5 chair stands (74%) had significantly greater strength. Walking speed was linearly associated with knee extensor strength over the entire range of strength, but its association with hip strength was limited to values below 15 kg. Time for five chair stands was associated with knee extensor and hip flexor strength below 10 and 15 kg, respectively, and no significant association was detected above these values. Stronger women were more likely to hold balance for 10 sec in the side-by-side, semi-tandem, and tandem positions. The percentage of the variance in performance explained by strength alone was always lower than 20%.

Conclusions. In this population, which does not include the strongest older women, there is a departure from linearity in the relationship between muscular strength and some measures of lower extremity performance.

R ECENT research has shown that older persons who perform poorly in standardized tests of lower extremity function are at high risk of developing incident disability (1,2). However, the basic process leading to reduction in lower extremity function and, in turn, loss of autonomy is still unclear. A number of physiologic and anatomic characteristics are important for lower extremity function, but their relative contribution to the frequent decline in performance observed in the older population is not well understood. Of particular interest is the role played by sarcopenia, a reduction in muscular mass that is often parallel to the aging process (3,4). While some impairments that cause reduction of lower extremity performance cannot be substantially influenced, studies have proved that the reduction

in strength induced by sarcopenia may be reversed by specific interventions (5–10).

It has been suggested that the relationship between measures of muscular function and performance on standardized tests of lower extremity function is particularly important in frail older persons with very low muscle strength (11–13). Training programs aimed at increasing muscular strength have been found to produce the greatest amount of improvement in function in very old, frail persons whose baseline muscle strength is in the lowest range (6,11–13). In stronger community-dwelling adults, resistance training may improve strength with little or no effect on gait speed (14). Identifying the limits within which muscle strength is strongly related to lower extremity performance may allow

for more effective targeting of older persons most likely to benefit from intervention programs aimed at improving muscular strength. This study uses data from the Women's Health and Aging Study (WHAS) to examine the form of the relationship between muscular strength and physical performance, and to identify possible departures from linearity that may have clinical implications.

METHODS

Study population. — This study uses data from the WHAS, a study jointly conducted by the Johns Hopkins Medical Institutions and the Epidemiology, Demography, and Biometry Program of the National Institute on Aging. The main objective of the WHAS is to study the causes and course of disability in the one-third most disabled older women living in the community (15).

An age-stratified random sample of 6,521 community-dwelling women aged 65 years and older, with oversampling of those over the age of 85 years, was selected from residents of the eastern half of Baltimore City and a small part of Baltimore County who were listed in the Health Care Financing Administration Medicare files. Of these, 5,316 were eligible for screening, and 4,137 participated in a screening interview and were assessed for physical and cognitive function. Cognitive function was assessed by the Mini-Mental State Examination (MMSE) (16). Disability was assessed by self-report of presence and level of difficulty in 15 activities, organized into the following four domains: mobility/exercise tolerance (walking one-quarter mile, walking up 10 steps without resting, getting in and out of bed or chairs, doing heavy housework); upper extremity abilities (raising arms over head, using fingers to grasp or handle, lifting and carrying 10 lb); basic self-care (bathing, dressing, eating, using the toilet); and higher functioning tasks of independent living (using the telephone, doing light housework, preparing meals, shopping for personal items) (17).

Overall, 1,409 women met a priori criteria for study eligibility, having difficulty in performing activities in two or more domains and scoring above 17 on the MMSE. Of these, 1,002 women agreed to participate in the full study. A detailed description of the study design, data collection methods, health, and functional status of the study population has been reported elsewhere (15). The WHAS baseline evaluation was conducted between November 1992 and February 1995 and included a comprehensive interview and a physical examination performed by specially trained nurses in the participants' homes. Analyses presented here are based on 985 women, after exclusion of 14 women who refused to undergo the examination measures and 3 women with bilateral amputations.

Measures of lower extremity muscular strength. — Maximum strength of the knee extensor and hip flexor muscles was assessed using a hand-held isometric dynamometer (Nicholas Manual Muscle Tester; model BK-7454, Fred Sammons, Inc., Burr Ridge, IL). Participants, seated in a hard chair with hips and knees flexed at 90 degrees, were asked to extend the knee (knee extension) or lift the knee (hip flexion), pushing as hard as they could against the dynamometer, which was positioned, respectively, a few inches above the ankle or immediately proximal to the femoral condyles at the distal thigh. Strength was measured as the peak force, expressed in kilograms force, that the examiner had to apply to break the isometric contraction, moving the subject's leg in the direction opposite to the voluntary movement. During the test the participant was allowed to place her hands on the front edge of the chair seat but not to lean backward. Examiners were trained extensively to standardize the method of data collection. Inter-rater reliability of these measures was assessed in a pilot study including 22 women. Intraclass correlation coefficients were .91 for knee extensor and .93 for hip flexor strength and were substantially unchanged, stratifying the analysis according to level of strength (< 15 kg vs ≥ 15 kg). The assessments were attempted only in women who could first perform the movements against gravity alone. Presence of casts and recent knee or hip surgery were exclusion criteria for specific tests. Also, measures obtained in participants who were bed-bound or who had difficulty sitting were not considered in this analysis. The best performance of two trials (knee) or three trials (hip) was selected for each side, and the averages of the left and right knee and the left and right hip, expressed in kilograms force, were used in the analysis.

Performance-based measures of lower extremity function. — Lower extremity function was evaluated using three performance-based tests that assessed walking speed, time to rise from a chair and sit down five times (chair stands), and standing balance (18).

Walking speed was assessed by having the participant walk at her usual pace over a 4-m course, except for 85 women who did not have adequate space in their homes, for whom a 3-m course was used. Participants were instructed to stand with both feet touching the starting line and to start walking after a specific verbal command. Timing began when the command was given, and the time needed to complete the entire distance was recorded. The average of two walks was used to compute a measure of walking speed. Use of aids (canes or walkers) was allowed for this test.

The test of repeated chair stands was performed using a chair found in the participant's home. The interviewer selected an armless, straight-back chair with a seat approximately 18 in high at the front edge. The average height of the seat was 17.5 ± 0.6 in (range 16–19 in). Participants were first asked to stand from a sitting position without using their arms. If they were able to perform this activity, they were then asked to stand up and sit five times as quickly as possible. The time to complete the entire task was recorded.

For tests of standing balance, subjects were asked to maintain balance in three positions characterized by a progressive narrowing of the base of support: feet together (side-by-side position), the heel of one foot beside the big toe of the other foot (semi-tandem position), and the heel of one foot in front of and touching the toes of the other foot

(tandem position). Only women who were able to maintain balance for 10 sec in one position were permitted to attempt the next, more difficult position.

Statistical analysis. — Statistical analysis was performed using the SAS (19) and the S-Plus statistical packages (20). Analyses were conducted with unweighted data because the stratification variable, age, was adjusted for in the analyses (21).

Differences in average values of muscular strength between subgroups of the study population were analyzed using analysis of variance. The independent effects of age, height, and weight on walking speed and time to complete five chair stands were first examined in linear regression models. The residuals from these models can be interpreted as performance results with the variability attributable to the covariates in the model removed. Plotting these values against measures of muscular strength permits the examination of the functional form of the strength-performance relationship, independent of the other covariates. Least-square linear regression lines and locally weighted regression smoothers (lowess) (22) were fitted to the data points of these scatterplots. Formal tests for differences between the linear fit and the local regression smoother fit were performed using nonparametric generalized additive models in which the linear function for muscular strength was replaced by a locally weighted regression smoother (22). Nonlinear relationships were summarized as multi-segmented lines by fitting piecewise linear regression models allowing different slopes for different ranges of muscular strength. The values of strength-defining intersection points between segments specified in these models were established by examining the shape of the local regression smoothers.

The relationship between muscular strength and balance was analyzed by fitting logistic regression models predicting the percent of persons who could maintain the side-by-side, semi-tandem, and tandem position for 10 sec as a function of muscular strength and other covariates. Ordinal variables for knee extensor and hip flexor strength were created for this analysis by dividing the range of strength (0–25 kg) into 10 equally spaced categories of 2.5 kg, each including the upper cutoff point. A few outliers with greater strength than 25 kg were included in the highest category. To evaluate whether the relationship between strength and the probability of completing each of the three balance tests was constant across the entire range of strength, the fit of models including a linear term for strength was compared to the fit obtained in models including a smoothed nonlinear function of strength, using a generalized additive model approach (22). A *p*-value less than .05 was considered as the cutoff point to establish statistical significance in all analyses.

The entire analysis was also repeated using values of muscular strength that were adjusted for age, height, and weight by a regression-based method, and again after normalizing knee extensor strength by knee height to estimate the moments developed. Results were substantially similar to those obtained using unadjusted measures of strength, and led to the same interpretation.

RESULTS

Overall, 90% of participants were tested for knee extensor and 87% for hip flexor strength (Table 1). Only 30 women were unable to perform the knee extensor strength test, and in 63 others the test was not performed for different reasons, primarily high blood pressure (Table 1). A slightly higher number of women were not tested for hip flexor strength (46 physically unable, 78 high blood pressure or other reasons).

Among women who were tested for muscular strength, the percentages who had valid data for the tests of walking speed, standing balance, and time to complete five chair stands are shown in Table 1. Results were virtually the same for the two measures of muscular strength. About three-quarters of the women who were tested for strength were able to walk the 4-m course without using aids, and close to one-quarter of them required the use of an aid. Among those women who had been tested for muscular strength, valid data for walking speed were available for more than 97%. In turn, among the same group of women, about 87% could maintain the side-by-side stand for at least 1 sec, and about 74% completed the five chair stand test.

The four histograms in Figure 1 show the distribution of performance on the tests of lower extremity function. Each bar represents the actual number of women who performed within specific ranges. The average walking speed was .58 ± .27 m/sec (range .06–1.67). Considered separately for women who used and did not use aids, the distributions of walking speed in these two subsets of the study population are quite distinct and significantly different ($F = 44.3$; $p < .0001$), but they do overlap. The average time to complete five chair stands was 15.7 ± 5.0 m/sec, with a distribution skewed to the right, no values under the threshold of 7 sec, and only a few women who required more than 40 sec to complete the test.

As expected, the score for the composite test of standing balance does not have a homogeneous distribution, with almost 50% of the data concentrated in the three values that are multiples of 10, indicating the successful completion of each of the subtests. About 70% of the women who attempted the side-by-side stand and did not attempt the tandem stand maintained the position for 10 sec. More than 45% of those who attempted the semitandem but not the full tandem stand maintained the semitandem position for 10 sec. Finally, more than 45% of those who attempted the tandem stand obtained the maximum score in the test, suggesting a relevant ceiling effect for this test even in this population of disabled women.

The associations between muscular strength and the ability to perform the three performance-based tests of lower extremity function are summarized in Figure 2. On average, knee extensor and hip flexor strength were 11.9 ± 4.9 and 10.5 ± 4.8 kg, respectively. The two histograms on the top row show the percent distributions of these two measurements. In both cases the distribution is almost symmetric, with a slight skewness to the right. The box plots show the distribution of muscular strength for each subgroup, defined by level of ability to perform the walking, the balance, and the five chair stand tests. Women unable to walk, who walked with an aid, who were unable to stand in the side-

Table 1. Ability to Perform Three Standardized Tests of Lower Extremity Function (Timed Walk, Balance, Five Chair Stands) in Women with Valid Measures of Knee Extensor and Hip Flexion Muscle Tests

| | Total (Total = 985) | | Valid Data for Walking Speed | | | | Valid Data for Standing Balance (n = 844) | | Valid Data for Five Chair Stands (n = 706) | |
| | | | Without Aids (n = 704) | | With Aids (n = 248) | | | | | |
Measures of Muscular Strength	n	%	n	%	n	%	n	%	n	%
Knee extensor strength										
Valid measures	892	90.3	660	74.0*	211	23.7*	777	87.1*	659	73.8*
One side only	46	4.7								
Both sides	846	85.6								
Unable to perform the test	30	3.0	11	36.7†	12	40.0‡	15	50.0†	9	30.0†
Physically unable	25	2.5								
Unable due to pain	5	0.5								
Test not done	63	6.4	33	35.5‡	25	39.7‡	52	82.5‡	38	57.6‡
High blood pressure	53	5.4								
Refusals	5	0.5								
Reason unknown	5	0.5								
Hip flexor strength										
Valid measures	861	87.4	649	75.4*	193	22.4*	756	87.8*	645	74.9*
One side only	61	6.2								
Both sides	800	81.2								
Unable to perform the test	46	4.7	13	28.3†	23	50.0†	25	54.3†	14	30.4†
Physically unable	45	4.6								
Unable due to pain	1	0.1								
Test not done	78	7.9	42	53.8‡	32	41.0‡	63	80.8‡	47	60.3‡
High blood pressure	58	5.9								
Unable to understand	3	0.3								
Refusals	3	0.3								
Reason unknown	14	1.5								

*Among those with valid measures of muscular strengths.
†Among those unable to perform the test of muscular strength.
‡Among those in whom muscular strength could not be assessed.

by-side position, and who were unable to do five chair stands had significantly lower ($p < .0001$) mean knee extension and hip flexion strength compared to those able to do these tests. However, the distributions of strength for performance subgroups largely overlap, especially for hip flexion. We could not identify a clear-cut threshold of strength for the ability to complete the three performance tests. However, it is possible that the ability to perform the muscular strength test is the only relevant threshold. In fact, some women who could be tested with the dynamometer, but had a strength as low as 2 kg, were able to walk, complete five chair stands, or maintain the side-by-side position.

Muscular strength, age, weight, and height were independent linear predictors of walking speed (Table 2). To examine the shape of the function in the scatterplot relating strength with speed, we used estimated values of walking speed adjusted for these covariates (Figure 3). Both the least-square regression line and the local weighted regression smoother suggest a linear association between knee extensor strength and walking speed. The variance in the dependent variable explained by the linear model including muscular strength was 30% (Table 2). Compared with the linear model, the improvement in fit obtained with the local regression model was not statistically significant.

For the hip flexor strength–walking speed relationship,

the local regression smoother suggests a departure from linearity (Figure 3), which is confirmed in the formal analysis (Table 2). In this instance, the form of the function relating strength and walking speed was further investigated using a piece-wise linear regression model. In this model the regression line is broken into two or more jointed segments, allowing for different slopes according to different values of muscular strength. Considering the trajectory of the smoothed line, the relationship was summarized as two segments with different slopes for knee extensor strength below 15 kg and above 15 kg. The results of fitting this model to the data are reported in the last column of Table 2. Below 15 kg of strength the slope is .016 m/sec/kg (almost double the slope estimated in the straight line model). Over the threshold of 15 kg the slope becomes .009, and it is no longer statistically significant, suggesting no effect of strength on walking speed. However, this result should be interpreted with caution because of the limited number of data points above this value. Compared with the linear model, the fit obtained by the piecewise regression model is significantly improved. However, the R^2 value has increased only from .21 to .24.

Age and weight, and difference between knee height and chair height (23), but not the subject's total height, were significant independent predictors of the time to complete
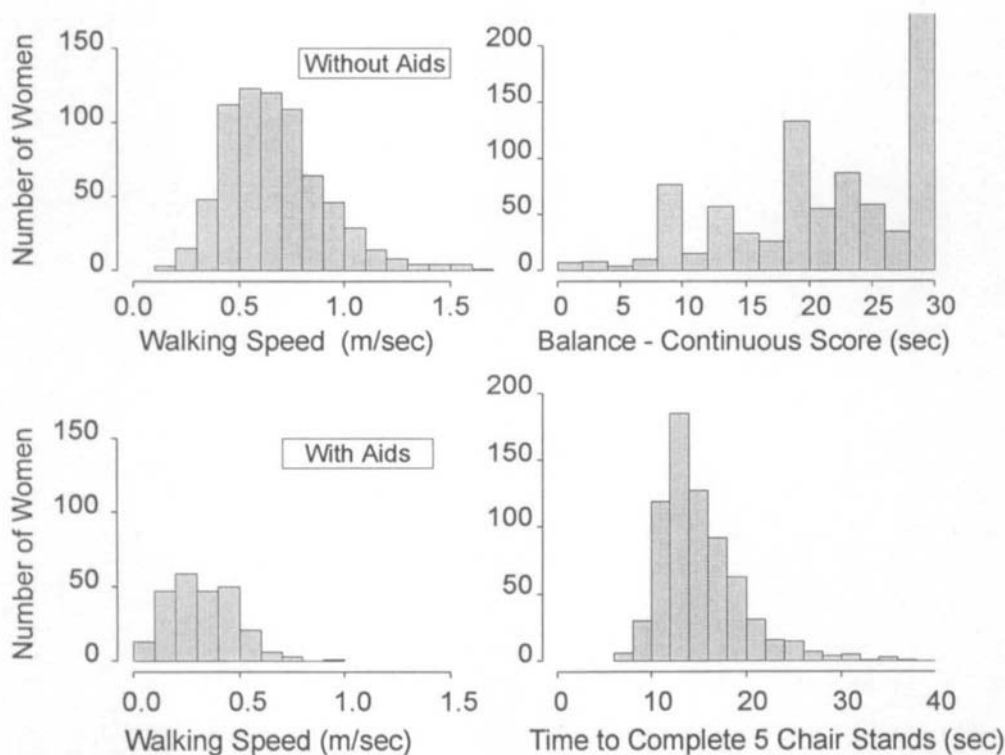
Figure 1. Histograms describing the results of the performance-based test of lower extremity function. The height of each bar represents the number of women who performed within a specific range. Walking speed is described separately according to use of aids during the test.
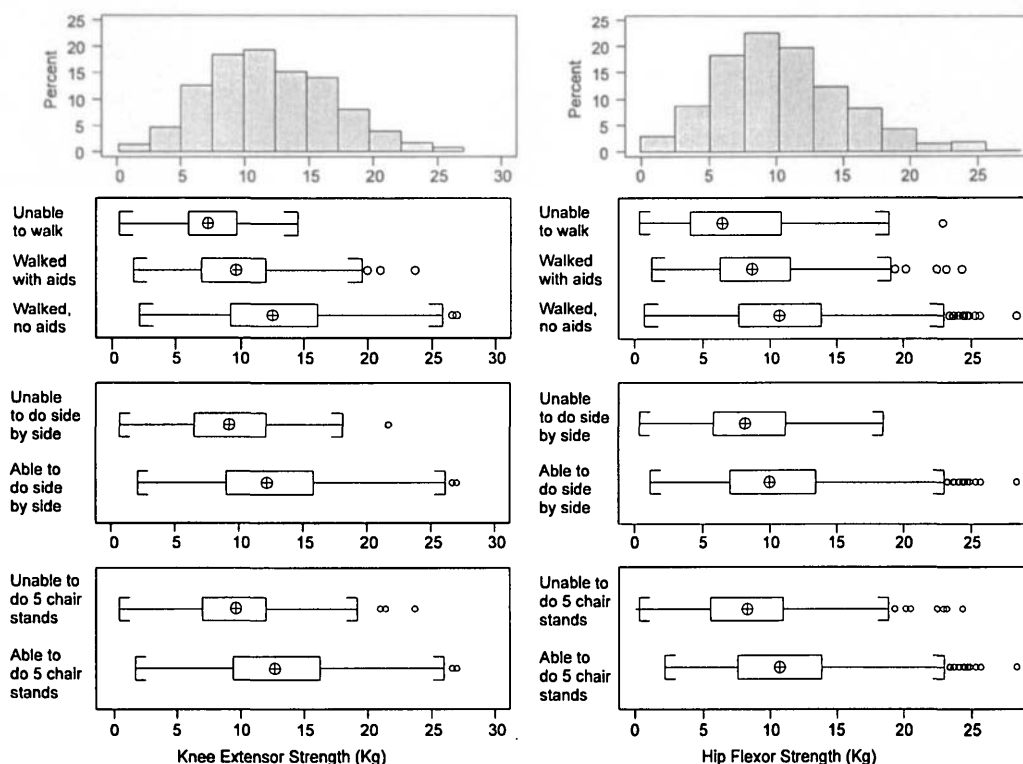

Figure 2. Distribution of knee extensor and hip flexor muscle strength for the total population and according to ability to perform standardized tests of walking speed, standing balance, and time to complete five chair stands. The cross in the box plot is the median. The box contains the values between the 25th and 75th percentiles (interquartile range). The brackets contain the full range of values, except values that are more than 1.5 times the interquartile range from the median, which are shown as open circles.

Table 2. Association Between Measures of Muscular Strength of the Lower Extremities
(Knee Extensor and Hip Flexor) and Walking Speed (m/sec)

Muscular Strength Test	Predictors (independent variables)	Linear Model (linear association over the entire range of strength)			Piecewise Linear Model (different slopes according to level of strength)		
		b	SE	p	b	SE	p
Knee extensor	Intercept	.563	.227	.012			
	Age (years)	–.011	.001	<.001			
	Height (cm)	.006	.001	<.001			
	Weight (kg)	–.003	.001	<.001			
	Strength (kg)	.018	.003	<.001*			
	R^2		.30				
	Test for nonlinearity		$p = .22$†				
Hip flexor	Intercept	.616	.245	.012	.571	.243	.018
	Age (years)	–.012	.001	<.001	–.012	.001	<.001
	Height (cm)	.007	.001	<.001	.006	.001	<.001
	Weight (kg)	–.003	.001	<.001	–.003	.001	<.001
	Strength (kg)	.010	.002	<.001*			
	Strength 1 (<15 kg)‡				.016	.002	<.001
	Strength 2 (>15 kg)				.009	.007	.420
	R^2		.21			.24	
	Test for nonlinearity		$p < .01$†		$F = 20.4; p < .001$§		

*Test for no independent association between strength and walking speed after adjusting for other covariates in the model.
†Chi-square test for difference between the linear fit and a local regression smooth fit based on Generalized Additive Model.
‡Strength value for intersection estimated from the locally weighted regression smoother (see Figure 3).
§F-test for difference between the linear fit and a piecewise regression fit allowing different slopes according to level of strength.
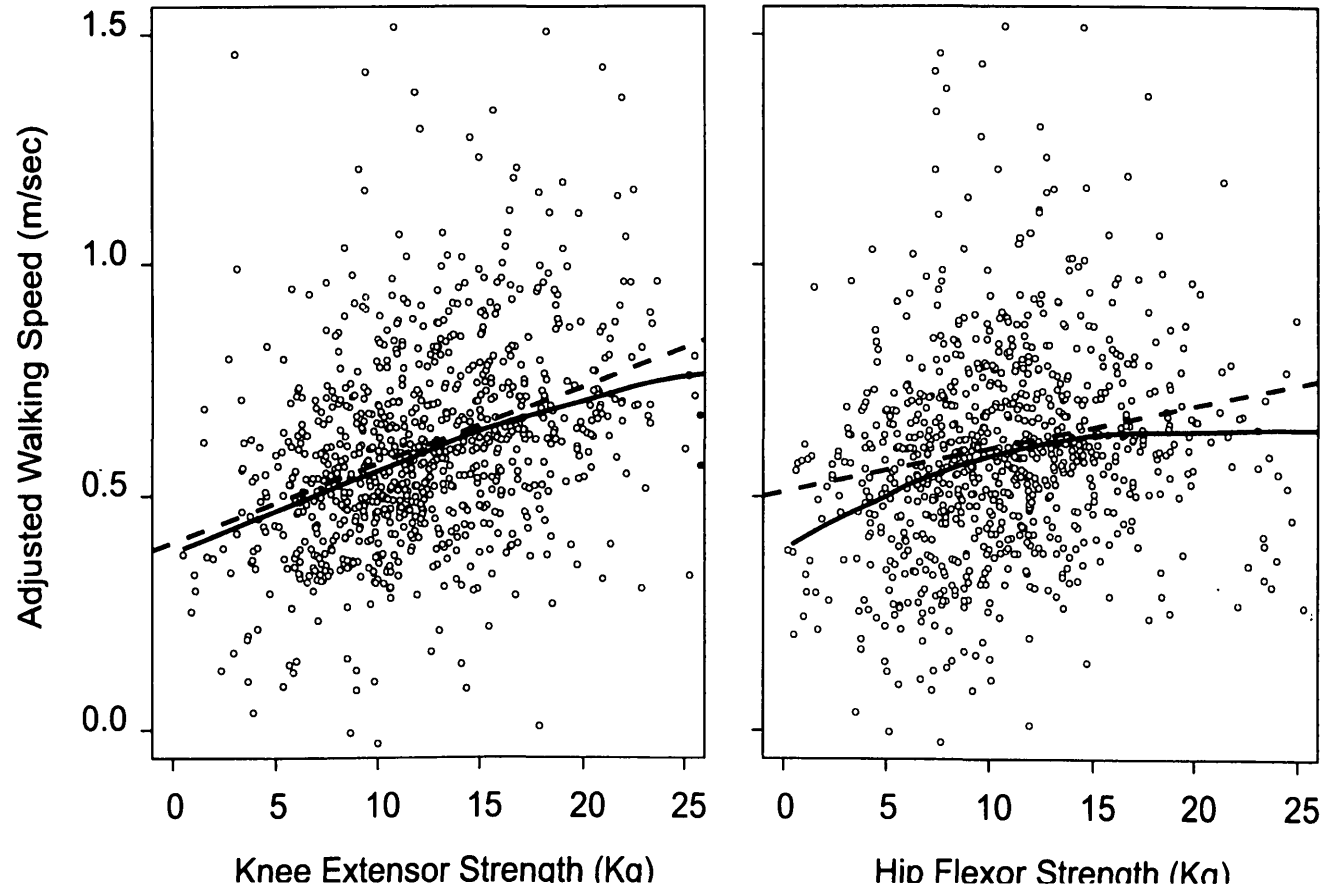

Figure 3. Relationship between knee extensor and hip flexor muscle strength and walking speed. The dashed line superimposed to the scatterplot is a least-square regression line. The solid line is a locally weighted regression smoother.

Table 3. Association Between Measures of Muscular Strength of the Lower Extremities
(Knee Extensor and Hip Flexor) and Time to Complete Five Chair Stands (sec)

Muscular Strength Test	Predictors (independent variables)	Linear Model (linear association over the entire range of strength)			Piecewise Linear Model (different slopes according to level of strength)		
		b	SE	p	b	SE	p
Knee extensor	Intercept	8.23	2.52	.001	12.44	2.67	<.001
	Age (years)	.11	.03	<.001	.11	.03	<.001
	Weight (kg)	.04	.01	<.001	.04	.01	<.001
	Difference knee-chair (cm)	.23	.06	<.001	.22	.06	<.001
	Strength (kg)	−.39	.04	<.001*			
	Strength 1 (<10 kg)‡				−.89	.12	<.001
	Strength 2 (>10 kg)				−.22	.16	.400
	R^2		.20			.23	
	Test for nonlinearity		$p < .001$†			$F = 18.4; p < .001$§	
Hip flexor	Intercept	4.32	2.67	.10	5.56	2.69	.040
	Age (years)	.13	.03	<.001	−.13	.03	<.001
	Weight (kg)	.04	.01	<.006	−.03	.01	<.012
	Difference knee-chair (cm)	.21	.07	<.004	.21	.07	
	Strength (kg)	−.20	.04	<.001*			
	Strength 1 (<15 kg)‡				.32	.06	<.001
	Strength 2 (>15 kg)				.13	.15	.547
	R^2		.10			.12	
	Test for nonlinearity		$p < .001$†			$F = 8.8; p = .003$§	

*Test for no independent association between strength and time to complete five chair stands after adjusting for other covariates in the model.

†Chi-square test for difference between the linear fit and a local regression smooth fit based on Generalized Additive Model.

‡Strength value for intersection estimated from the locally weighted regression smoother (see Figure 3).

§F-test for difference between the linear fit and a piecewise regression fit allowing different slopes according to level of strength.
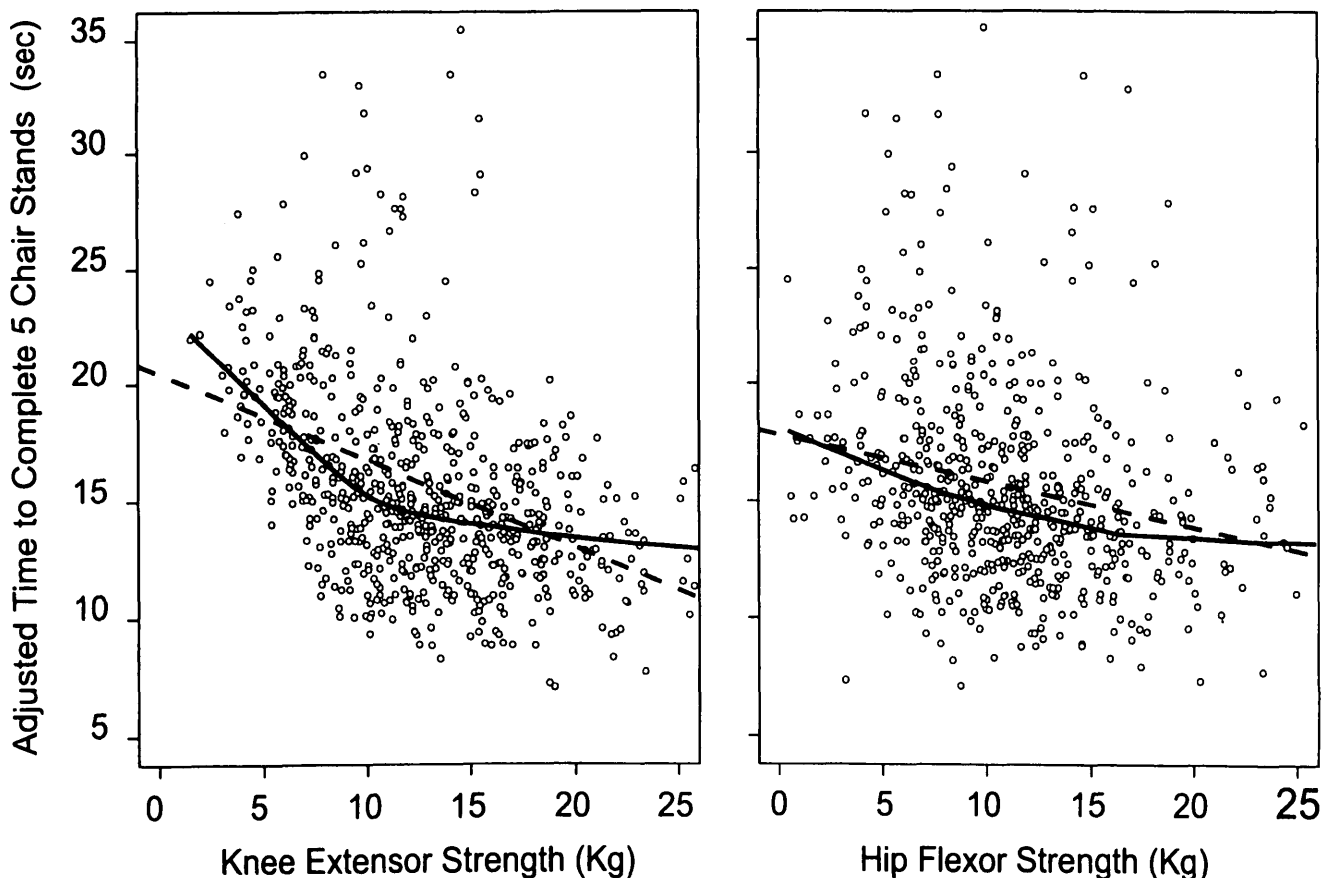

Figure 4. Relationship between knee extensor and hip flexor muscle strength and the time to complete five chair stands. The dashed line superimposed to the scatterplot is a least-square regression line. The solid line is a locally weighted regression smoother.
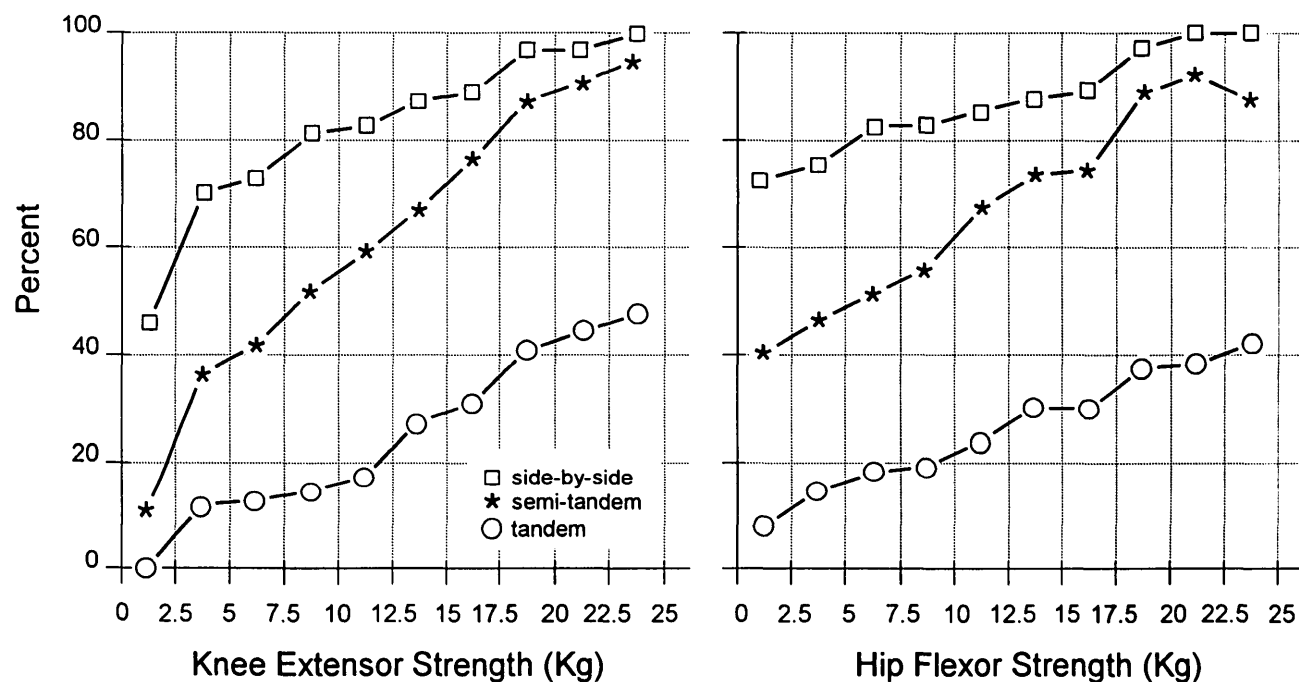
Figure 5. Relationship between knee extensor and hip flexor muscle strength and performance in the balance test, expressed as percent of women who could maintain for 10 sec the side-by-side, semi-tandem, and tandem stands. For this analysis strength as an ordinal measure was created by dividing the range of strength (0–25 kg) in 10 equidistant intervals.

Table 4. Association Between Measures of Muscular Strength of the Lower Extremities (Knee Extensor and Hip Flexor) and Performance in Balance, Expressed as Percent of Women Who Could Maintain for 10 secs the Side-by-Side, Semi-Tandem, and Tandem Positions

Muscular Strength Test	Predictors	Side-by-Side		Semitandem		Tandem	
		Odds-Ratio	95% C.I.	Odds-Ratio	95% C.I.	Odds-Ratio	95% C.I.
Knee extensor	Age	.90	.87– .93	.89	.87– .92	.85	.83– .88
	Weight (kg)	1.00	.98–1.01	.98	.97– .99	.98	.97– .99
	Strength (Δ of 2.5 kg)	1.26*	1.12–1.43	1.41*	1.29–1.55	1.26*	1.14–1.38
Hip flexor	Age	.90	.87– .93	.90	.88– .92	.85	.83– .88
	Weight (kg)	1.00	.98–1.01	.99	.98–1.00	.99	.98– .99
	Strength (Δ of 2.5 kg)	1.13*	1.00–1.28	1.29*	1.18–1.42	1.13*	1.03–1.24

*Effect of a linear term for muscular strength in the model predicting the percent of women who could complete each of the three balance tests. No improvement in the fit could be obtained by substituting a smoothed function of strength for the linear term.

five chair stands (Table 3). After adjusting for these variables, we found a significant association between strength and performance: stronger for knee extension than for hip flexion (Table 3). The use of a local regression smoothed line (Figure 4) significantly improved the fit for both muscular groups, and, therefore, the relationship was summarized using two-segment piecewise models, with intersections at 10 kg for knee extension and 15 kg for hip flexion (Table 3). Under these threshold values the slopes estimated by these models were -.89 sec/kg and -.32 sec/kg, respectively. Above 10 kg of knee extensor strength and 15 kg of hip flexor strength the regression coefficients become smaller and are no longer statistically significant. Comparing the linear to the piece-wise regression models, for knee extensor strength the percent of variance explained in the time to complete five chair stands increases from 20% to 24%, and for hip flexor strength it increases from 10% to 12%.

The percentage of persons who could maintain the semi-tandem and tandem stands for 10 sec decreased progressively with increasing age and weight, while age but not weight was independently associated with performance in the side-by-side stand (Figure 5 and Table 4). After adjusting for these covariates, we found that increased strength was associated with a higher proportion of women who could successfully complete each of the three balance tests. For knee extensor strength, the odds-ratio of completing the test associated with an increase in strength of 2.5 kg was 1.26 for the side-by-side stand, 1.41 for the semitandem stand, and 1.26 for the tandem stand. For hip flexor strength these estimates were 1.13, 1.29, and 1.13, respectively. When examined in formal tests, the small departures from linearity apparent in Figure 5 were not statistically significant. Therefore, this means that the above-mentioned odds-ratios for successfully completing the tests associated with

a difference in strength of 2.5 kg should be considered valid across the entire range of strength. Interestingly, the size of the coefficient for strength is larger in the model for semitandem stand than in the models for the other two stands, although the confidence intervals estimated for the effects of strength in the three models overlap (Figure 5 and Table 4).

DISCUSSION

The analyses presented in this article examine the relationship between hip flexor and knee extensor muscle strength and performance on standardized tests of lower extremity function in a population-based sample of older women affected by chronic disease and functional limitations. For all three measures of physical performance, women who could be tested were significantly stronger than women who were unable to do the performance test, but there was a substantial overlap in the distributions of strength between these two groups. Some women with very low strength could walk without using aids, could complete five chair stands, and could successfully maintain their balance. These results suggest that these three standardized tasks need very minimal strength to be performed, especially when strength is the only limiting factor, and that there is not a clear-cut strength threshold for ability versus inability to perform these tests in this population.

Consistent with most published research (11,13,24–29), muscular strength was a significant predictor of all three measures of performance. This association was independent of age and anthropometric characteristics, such as weight and height. The functional form of the relationships of strength with walking speed and with time to complete five chair stands was, overall, not linear. Hip flexor strength was a significant predictor of walking speed or time to complete five chair stands only below 15 kg, and knee extensor strength was associated with time to complete five chair stands only below 10 kg. Above these values, greater strength was not significantly related to better performance. However, the relationship between knee extensor strength and walking speed was linear over the entire range of strength.

Previous studies have hypothesized the existence of a threshold below which reduction in strength is associated with progressive decrements in lower extremity performance and suggested that above this threshold increments in strength substantially improve physiologic reserve but have only minimal effects on actual performance. These studies were performed in relatively healthy populations that included only small numbers of persons with impairments or disabilities (9,30). To the best of our knowledge, this is the first study demonstrating a departure from linearity in the relationship between muscular strength and performance of lower extremity function in a large, representative sample of the old, most disabled, and presumably weakest portion of the population.

Compared to the findings of other studies (9,26,27,30), the percent of variance in walking speed and chair stand time explained by muscular strength was relatively small. Figures 3 and 4 show a fair amount of variability around the regression lines. These findings strongly indicate that

the decline in physical functioning, and in particular lower extremity performance, cannot be attributed to a single causal pathway. Many age-associated changes other than muscular strength that may potentially influence lower extremity performance have a high prevalence in this population of disabled women (15). These factors, which include medical conditions, health-related behaviors, psychological well-being, and socioeconomic status, may play a complex and mutually interactive role in the causal pathway leading to physical decline in old age. Given this complexity, it is perhaps surprising that we were able to detect, examine the form of, and formally test the relationship between muscular strength and lower extremity performance in this population. We believe that studying single relationships is an essential step in the direction of disentangling the complexity of the causal pathway leading to disability in old age. Only after the individual effects of the most important factors are better understood will it be possible to evaluate how they mutually interact to cause reduction in performance.

Increasing strength was found to be associated with a progressively higher percentage of women who could maintain the three hierarchical tests of standing balance for 10 sec. The same difference in strength had a similar impact on the probability of successfully maintaining balance over the entire range of strength. The lack of a threshold effect in the relationship between muscular strength and performance in standing balance is somewhat unexpected since, physiologically, the strength needed to maintain balance is minimal and strength above this level would seem to offer no advantage in the maintenance of balance. However, older subjects are often affected by multiple pathologic conditions, such as visual impairments, peripheral neuropathy, and vestibular problems, that interfere with balance control. In these persons it is likely that increased strength is necessary to counteract these destabilizing factors, especially when stable balance should be maintained for a period of time. This may explain why we did not find a threshold of strength for the ability to maintain the side-by-side position for at least 1 sec, while we found a strong relationship between muscular strength and the ability to maintain balance in the three standing positions for the full 10 sec. These findings are consistent with recent studies demonstrating that high-intensity exercise improves balance in older persons (8).

Some of the results of analyses of standing balance deserve specific comment. Weight was a significant negative predictor of the ability to successfully complete the semitandem and tandem, but not the side-by-side, stand. In the side-by-side stand there is a stable base of support, lateral sway is limited to narrow oscillations, and, therefore, maintenance of balance only requires a small amount of active muscle contraction (31). When the base of support becomes more unstable, moving from the side-by-side to the semitandem and the tandem stands, the amplitude of lateral sway tends to increase (32), and the neuromuscular resources (postural neurologic reflexes and muscular strength) needed to maintain balance are probably proportional to the mass that must be moved (31).

It is interesting that, among the three standing positions

used in this study to evaluate balance, the semitandem stand was the most influenced by muscular strength. Compared with the other two stands the difference is small, and the confidence interval of the regression coefficients shows some overlap. However, less than 10% of women with knee extensor strength between 0 to 2.5 kg were able to maintain the semitandem stand, while almost 100% of those with strength higher than 22.5 kg could maintain this position for 10 sec. An important difference between the semitandem stand and the other, more challenging (tandem) and less challenging (side-by-side) positions is that the semitandem is the only stand that is not symmetric in the sagittal plane. Further studies are needed to confirm our finding and to verify whether muscular strength is a more critical factor in maintaining balance in nonsymmetrical postures. This information may be important to our understanding of the potential effectiveness of increasing muscular strength to improve balance in the older population.

Overall, our findings show that in the lower range of the spectrum of strength, strength is associated with all measures of lower extremity performances, while the relationship above this threshold is limited to only some of these performance measures. This suggests that the role played by reductions of muscular strength in the disabling process is particularly important in the more frail part of the population (11,30) and is consistent with the observation that high intensity resistance exercise programs are particularly beneficial in old and physically frail persons (6,7,14). However, our results should be confirmed in studies in which multiple measures of muscular strength and lower extremity performance are collected over time in the same person.

The three lower extremity performance tasks used in this study were originally chosen with the idea that one is mainly a balance task (stands), one is mainly a strength task (chair), and one is a direct measure of gait (18). However, data from this study suggest that muscular strength is important for all three of these tasks, in somewhat different ways. Consequently, despite the nonlinearity of some relationships, our findings suggest that interventions aimed at improving strength will potentially be effective in a significant proportion of women with similar characteristics to those in the WHAS study population. Depending on the initial level of strength, the effects of these interventions may be detected only by using specific performance-based measures. Future studies are needed to verify how the magnitude of improvement in performance achievable by exercise training in older persons compares with the magnitude of improvement that is predicted by observational studies. In fact, a certain amount of functional gain may be obtained through the use of compensatory motor strategies that become possible only after improvement in strength.

We believe that the findings of this study also have important implications for clinical assessment. There are inherent limitations in using measures of muscular strength in the clinical evaluation and follow-up of elderly patients. Available techniques are complex, standardization is difficult and time consuming, and, finally, muscular strength is only one of the many possible causes of reduction in lower extremity performance (33,34). As an alternative, we propose a diagnostic strategy appropriate for geriatrics that is based on a combination of first-line performance tests, used extensively for screening and follow-up, and complemented by second-line, more complicated and time-consuming measures of specific impairments, such as measures of muscular strength. These tests would be administered only in persons with poor performance or in those in whom performance has recently declined. This strategy may help to identify groups of individuals at high risk of adverse outcomes and then, using further tests, to select the most effective strategies for interventions. For example, in disabled persons who have good muscle strength, interventions other than strength training may offer greater benefit. Given the complexity of the multifactorial causal pathway leading from diseases to disability in the older population, we need a great deal more information before such a strategy can be fully implemented.

REFERENCES

1. Gill TM, Williams CS, Tinetti ME. Assessing risk for the onset of functional dependence among older adults: the role of physical performance. J Am Geriatr Soc 1995;43:603–9.
2. Guralnik JM, Ferrucci L, Simonsick EM, Salive ME, Wallace RB. Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability. N Engl J Med 1995;332:556–61.
3. Evans JW. What is sarcopenia? J Gerontol 1995;50A (Special Issue):5–8.
4. Grimby G. Muscle performance and structure in the elderly as studied cross-sectionally and longitudinally. J Gerontol 1995;50A (Special Issue):17–22.
5. Fiatarone MA, Evans WJ. The etiology and reversibility of muscle dysfunction in the aged. J Gerontol Med Sci 1993;48:M77–83.
6. Fiatarone MA, O'Neill EF, Ryan ND, Clements KM, Solares GR, Nelson ME, Roberts SB, Kehayias JJ, Lipsitz LA, Evans WJ. Exercise training and nutritional supplementation for physical frailty in very elderly people. N Engl J Med 1994;330:1769–75.
7. Fiatarone MA, Marks EC, Ryan ND, Meredith CN, Lipsit LA, Evans WJ. High-intensity strength training in nonagenarians: effects on skeletal muscle. JAMA 1990;263:3029–34.
8. Judge JO, Lindsey C, Underwood M, Winsemius D. Balance improvements in older women: effects of exercise training. Phys Ther 1993;73:254–62
9. Judge JO, Underwood M, Gennosa T. Exercise to improve gait velocity in older persons. Arch Phys Med Rehabil 1993;74:400–6.
10. Ades PA, Ballor DL, Ashikava T, Utton JL, Nair KS. Weight training improves walking endurance in healthy elderly persons. Ann Intern Med 1996;124:568–72.
11. Buchner DM, deLateur BJ. The importance of skeletal muscle strength to physical function in older adults. Ann Behav Med 1991;13:91–8.
12. Buchner DM, Beresford SAA, Larson EB, LaCroix AZ, Wagner EH. Effects of physical activity on health status in older adults II: intervention studies. Annu Rev Public Health 1992;13:469–88.
13. Young A. Exercise physiology in geriatric practice. Acta Med Scand 1986;711:227–32.
14. Buchner DM, Cress ME, Esselman PC, et al. The effect of strength and endurance training on gait, balance, fall risk, and health services use in community living older adults. J Gerontol Med Sci 1997; 52A:M218–24.
15. Guralnik JM, Fried LP, Simonsick EM, Kasper JD, Lafferty ME. The Women's Health and Aging Study. Health and social characteristics of

older women with disability. NIH pub. no. 95-4009, Bethesda, MD: National Institute on Aging, 1995.

16. Folstein MF, Folstein S, McHugh PR. Mini-Mental State: a practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res 1975;12:189–98.

17. Fried LP, Ettinger WH, Hermanson B, Newman AB, Gardin J. Physical disability in older adults: a physiological approach. J Clin Epidemiol 1994;47:747–60.

18. Guralnik JM, Simonsick EM, Ferrucci L, Glynn RJ, Berkman LF, Blazer DG, Scherr PA, Wallace RB. A short physical performance battery assessing lower extremities function: association with self-reported disability and prediction of mortality and nursing home admission. J Gerontol Med Sci 1994;49:M85–94.

19. SAS Institute Inc. SAS procedures guide, version 6. Cary, NC: SAS Institute, 1993.

20. Statistical Sciences, S-PLUS guide to statistical and mathematical analysis, version 3.3. Seattle: StateSci, a division of MathSoft, Inc., 1995.

21. Korn EL, Graubard BI. Epidemiologic studies utilizing surveys: accounting for the sampling design. Am J Public Health 1991;81: 1166–73.

22. Hastie TJ, Tibsherani RJ. Generalized additive models. London: Chapman & Hall, 1994.

23. Weiner DK, Long R, Hughes MA, Chandler J, Studenski S. When older adults face the chair-rise challenge: a study of chair height availability and height-modified chair-rise performance in the elderly. J Am Geriatr Soc 1993;41:6–10.

24. Alexander NB, Schultz AB, Warwick DN. Rising from a chair: effects of age and functional ability on performance biomechanics. J Gerontol Med Sci 1991;46:M91–8.

25. Brown MB, Sinacore DR, Host HH. The relationship of strength to function in the older adult. J Gerontol 1995;50A (Special Issue):55–9.

26. Wolfson L, Judge J, Whipple R, King M. Strength is a major factor in balance, gait, and the occurrence of falls. J Gerontol 1995;50A (Special Issue):64–7.

27. Bassey EJ, Fiatarone MA, O'Neil EF, Kelly M, Evans WJ. Leg extensor power and functional performance in very old men and women. Clin Sci 1992;82:321–7.

28. Chang RW, Dunlop D, Gibbs J, Hughes S. The determinants of walking velocity in the elderly: an evaluation using regression trees. Arthritis Rheum 1995; 38:343–50.

29. Gibbs J, Hughes S, Dunlop D, Singer R, Chang RW. Predictors of change in walking velocity in older adults. J Am Geriatr Soc 1996;44:126–32.

30. Buchner DM, Larson EB, Wagner EH, Koepsell TD, deLauter BJ. Evidence for a nonlinear relationship between leg strength and gait speed. Age Ageing 1996;25:386–91.

31. Enoka RM. Neuromechanical Basis of Kinesiology. Champain, IL: Human Kinetics Books, 1988.

32. Day BL, Steiger MJ, Tompson PD, Marsden CD. Effect of vision and stance on human body motion when standing: implication for afferent control of lateral sway. Physiol 1993;469:479–99.

33. Fife TD, Baloh W. Disequilibrium of unknown cause in older people. Ann Neurol 1993;34:694–702.

34. Bohannon RW. Standing balance, lower extremity muscle strength, and walking performance of patients referred for physical therapy. Percept Mot Skills 1995;80:379–85.