

Longitudinal Muscle Strength Changes in Older Adults: Influence of Muscle Mass, Physical Activity, and Health

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The longitudinal changes in isokinetic strength of knee and elbow extensors and flexors, muscle mass, physical activity, and health were examined in 120 subjects initially 46 to 78 years old. Sixty-eight women and 52 men were reexamined after 9.7 ± 1.1 years. The rates of decline in isokinetic strength averaged 14% per decade for knee extensors and 16% per decade for knee flexors in men and women. Women demonstrated slower rates of decline in elbow extensors and flexors (2% per decade) than men (12% per decade). Older subjects demonstrated a greater rate of decline in strength. In men, longitudinal rates of decline of leg muscle strength were $\sim 60\%$ greater than estimates from a cross-sectional analysis in the same population. The change in leg strength was directly related to the change in muscle mass in both men and women, and it was inversely related to the change in medication use in men. Physical activity declined yet was not directly associated with strength changes. Although muscle mass changes influenced the magnitude of the strength changes over time, strength declines in spite of muscle mass maintenance or even gain emphasize the need to explore the contribution of other cellular, neural, or metabolic mediators of strength changes.

THE ability to perform normal daily household, work related, and recreational activities is determined in part by the force-generating capacity of skeletal muscles. Muscle strength may display decremental changes with age such that a particular activity may become increasingly harder (lifting a bag of groceries), or strength may reach a threshold such that an activity can no longer be performed (e.g., standing up from a chair without assistance). Impairments in muscle strength are associated with falls, decreased mobility, walking speed, functional dependence, and disability (1). An analysis of the longitudinal changes in upper and lower extremity muscle strength in an older adult population, in concert with factors expected to influence muscle strength, will lend insight into the relative importance of these factors in the maintenance of muscle strength as people age and will help in the design of interventions that can prevent the decline.

Maximal dynamic force production by muscle groups of the upper and lower extremities declines with age (2–4). However, estimates of the rates of decline are mainly derived from cross-sectional studies and may not represent the true age-related changes in strength. The best estimates of

longitudinal decline in muscle function in the older adult are derived from measures of grip strength or isometric strength of arm muscles (5–9). To our knowledge, there are no published studies comparing longitudinal rates of decline in dynamic strength in muscle groups of the lower and upper extremities in the same population. In general, longitudinal studies of lower body muscle strength have been limited by small sample sizes (<40), few females subjects (42 women in three studies), and a large loss to follow-up ($>53\%$), thereby potentially misrepresenting the true population changes (9–13).

Additionally, physiologic, health- or exercise-related factors contributing to changes in strength have been minimally addressed in previous longitudinal studies. The decline in contractile tissue is strongly related to declines in function in cross-sectional analyses. However, longitudinal studies of strength and muscle mass do not always reach the same conclusion, suggesting potential roles for other age-related neuromuscular changes. Chronic disease prevalence is significantly associated with muscle weakness in cross-sectional analyses (14,15). However, the impact of the natural progression of chronic disease on muscle strength has re-

ceived little attention. Studies in active older adults suggest that activity can attenuate many of the declines in various domains of physical function. Yet, aside from exercise-intervention studies, the role of habitual leisure time physical activity in maintaining muscle function in elderly subjects is still unclear.

The purpose of this study was to examine the change in muscle strength of the knee and elbow extensors and flexors in older men and women over a period of 10 years. Because of selection bias in cross-sectional studies, we hypothesize that rates of changes of muscle strength measured longitudinally will be greater than those measured in the same sample by using a cross-sectional analysis. We also hypothesize that the change in strength is significantly related to a change in whole body muscle mass over the follow-up period and that a maintenance or increase in physical activity, compared with a decrease in physical activity, will attenuate the decline in strength loss.

METHODS

Design and Subjects

The subjects in this study originally participated in a cross-sectional study from 1985 to 1988 to assess muscle strength and body composition in men and women aged 45 to 78 years (2). Subjects were contacted again to determine their interest in returning for a follow-up study. Searches at the Massachusetts Department of Vital Statistics, Massachusetts Department of Motor Vehicles, of the Social Security Death Index (16), and of telephone directories were used to locate individuals who were no longer living at their original address.

Of the original cohort ($n = 190$, 53% female), 64% returned for testing, 17% were not interested in testing but did consent to answering a variety of questionnaires, 6% were dead, and 13% were not located. For individuals who refused follow-up testing, the reasons cited for not returning were as follows: moved too far to come in for testing ($n = 9$), no time ($n = 6$), unknown ($n = 6$), medical issues ($n = 4$), "too old" ($n = 2$), testing too stressful ($n = 2$), risks associated with testing ($n = 1$), no health insurance ($n = 1$), and in nursing home ($n = 1$).

Subjects were screened at both occasions by a medical history, physical examination, analysis of standard blood and urine chemistries, and an electrocardiogram. The subjects recruited for the baseline evaluation were community dwelling and did not have medical conditions or take medications known to interfere with neuromuscular function or testing. The only exclusion criteria for the follow-up examination were terminal illness and cognitive impairment that prevented informed consent. The study design and procedures were approved by the Human Investigation Review Committee of Tufts–New England Medical Center. All procedures were explained to the volunteers, and written informed consents were obtained prior to the study. Each subject was paid a stipend for participation in this study.

Study Procedures

In order to control for possible seasonal influences on muscle strength and body composition at follow-up, sub-

jects were studied at the same time of year as their baseline visit in the mid-1980s (17,18). Tests were also performed at the same time of day during both evaluations. All tests described below were performed over a 2-day residential period in the Metabolic Research Unit (MRU) of the Jean Mayer USDA Human Nutrition Research Center on Aging at Tufts University.

Isokinetic strength.—Measurements of isokinetic strength were made at 60°/s by using testing protocols, calibration procedures, and equipment (Cybex II with Cybex Data Reduction Computer, Cybex Inc., Medway, MA) identical to those used for the baseline assessment (2). During the testing of the knee joint, the lever arm was attached to the tibia and its axis of rotation was aligned with the anatomic axis of rotation of the knee joint. Straps were used to stabilize the trunk, hip, and thigh. The hip joint was at an angle between 90° and 100° of flexion during testing. The elbow extensors and flexors muscle groups were tested with the volunteers in a supine position and restrained with a strap at the level of the pelvis. The arm was positioned in 45° of abduction. The volunteers were instructed to keep their wrists locked in a neutral position throughout the movement. The rotational axis of the lever arm was aligned with the axis of rotation of the elbow joint. Volunteers were not permitted to raise their arms or shoulders off the table during testing. Torque of the knee extensors and flexor muscle groups was corrected for the effects of gravity by using algorithms supplied with the Cybex software. No gravitational adjustments were made for arm measurements. During the first study, two measurements of isokinetic strength were made 10–14 days apart. For the follow-up study, two measurements of strength were made on consecutive days. At the baseline and follow-up assessments, the highest value obtained from each session for each muscle group was used in the data analysis. One tester performed all tests during the follow-up examination and was trained by one of the testers from the first evaluation. Muscle strength is reported as the average of the nondominant and dominant sides.

Muscle mass.—A subset of the subjects tested in the mid-1980s collected 24-hour urine samples for the measurement of creatinine for estimation of skeletal muscle mass. All subjects collected 24-hour urine samples during the follow-up study. Ninety-one subjects (51 women and 40 men) had complete urine creatinine data from both evaluations. Subjects were given instructions to follow a creatine- or creatinine-free diet for 3 days prior to the start of the urine collections and continued the meat-free diet during the supervised collection period in the MRU. Urine creatinine was measured by using a commercially available kit based on the method of Larson (19). Muscle mass was estimated by multiplying the mass (in grams) of creatinine excreted in 24 hours by 18.5 (20). The coefficient of variation for consecutive day measurements is 6.4% in our laboratory.

Physical activity.—Physical activity was assessed by using the Alumni Health Physical Activity Questionnaire to assess participation in sports and recreational activities over the previous 12 months (21). All subjects during the first

and follow-up assessment were queried in an open-ended fashion by the same investigator. Total kilocalories per year of energy expenditure in each activity were calculated by using total minutes in each activity, body weight, and metabolic (MET) levels from standard tables (22). Average weekly energy expenditure was calculated as the sum of the energy expenditures of individual activities divided by 52 weeks. Subjects with low activity levels were defined as those expending on average less than 500 kcal/wk over the past year. This level was chosen because of its association with increased prevalence of chronic diseases (see, e.g., 23). Subjects participating in resistance-type exercises at least 40 weeks out of the year were classified as resistance trained. The coefficient of variation for repeated assessments 2 weeks apart was 2% (test-retest correlation coefficient: $r = .98, p < .02$).

Assessment of health and functional status.—Medical records were reviewed from the baseline and follow-up exams to extract medication use, symptoms, and self-reported medical conditions at both evaluation time points. One physician coded all medical conditions. Physical disability was assessed only at follow-up by using a scale that measured the difficulty of doing 26 activities of daily living (24). A history of falls in the past year was assessed at follow-up only (25).

Data Analysis

Statistical analyses were performed by using SYSTAT for Macintosh, Version 5.2.1 and SYSTAT for Windows, Version 7.0.1 (SPSS Inc., Chicago, IL). The data are reported as mean \pm standard deviation (SD), median, or range. An analysis of variance was used to assess baseline differences between subject groups classified according to follow-up status (returned for testing, declined testing, deceased, or not located). A repeated measures analysis of variance was used to assess time and gender differences in strength changes for each muscle group, and for changes in body weight, muscle mass change, and physical activity. Percent changes in the strength variables were calculated as the [(change/baseline value)/follow-up years] \times 100 and then multiplied by 10 (to represent changes per decade). Percent changes in strength between genders were tested by using a Student's t test for independent samples. Paired t tests were used to compare muscle group strength declines within genders. A multiple regression analysis was used to assess significant determinants of percent strength changes, adjusted for gender and interaction terms. Quartiles of physical activity were determined separately in men and women at baseline. An analysis of covariance, adjusting for age and gender, was used to compare strength changes between those becoming more sedentary (moving to a lower quartile) to all other subjects (those who did not change quartile of activity level). The cross-sectional change in strength at baseline was examined by using an analysis of covariance with sex as a factor and age as a covariate only for subjects studied at both the baseline and follow-up assessments. One-sample t tests were used to compare the mean of the individual longitudinal changes to the estimated cross-sectional change. Results were judged to be statistically significant

when the two-sided observed significance level (p value) was less than .05.

RESULTS

The average length of follow-up for subjects returning for testing was 9.7 ± 1.1 years with a range of 7.9–12.6 years. All subjects returning for testing were community dwelling. Sixty-eight percent of the initial female cohort and 58% of the initial male cohort returned for testing. The subject population was 98% Caucasian. At follow-up, all subjects were able to complete the muscle strength assessments.

A comparison of baseline characteristics of subjects categorized by follow-up status (returned for testing, declined testing, deceased, or not located), indicates that the group that returned for testing was similar to those deceased or not located in their baseline age, knee, and elbow strength. The subjects who declined repeat testing were initially older by 5 years ($p < .05$), weaker (11% in knee extensors and 5% in elbow flexors), and reported more medical conditions (1.8 ± 0.7 vs 1.5 ± 0.8) than the subjects who returned for testing ($p < .05$). They also had a more dependent functional status score (0.24 ± 0.48 vs 0.10 ± 0.21 ; $p < .03$) at follow-up.

Subject characteristics from the baseline evaluation for those returning for follow-up assessment are presented in Table 1. The average age at follow-up was 70.1 ± 7.7 years. At follow-up, 19% of men and 40% of women reported living alone; 23% of men and 34% of women reported some functional impairment on the NHANES I Functional Status Survey (median scores and range for all men of 0.13, 0–0.5; for all women of 0.13, 0–1). Twenty-three percent of men and 28% of women reported at least one fall during the last year.

Muscle Strength

Men had greater strength on average than women in all muscle groups initially and at follow-up ($p < .001$; Table 2). All muscle groups declined in strength over time ($p < .001$). A significant time by gender interaction ($p < .05$ –.001, for all muscle groups) reflected the greater *absolute* loss of strength for each muscle group in men compared with that in women. *Percent* losses per decade for elbow strength were also greater in men than in women ($p < .05$). However, *percent* changes in knee extensor and flexor strength losses were similar in men and women and ranged 11.1–16.7% over the follow-up period.

A comparison of the upper versus lower body strength loss in antigravity muscles demonstrates that women had a greater loss ($p < .001$) in knee extensor strength than in elbow flexion strength, whereas men demonstrated similar

Table 1. Baseline Subject Characteristics for Those Returning for Testing

Parameter	Women	Men
<i>n</i>	68	52
Age (y)	60.4 ± 7.4	60.4 ± 7.9
Weight (kg)	65.0 ± 11.2	77.0 ± 8.8
Body mass index (kg/m ²)	24.7 ± 3.8	25.1 ± 2.7
Medications/day (no.)	0.4 ± 0.7	0.3 ± 0.5
Chronic medical conditions (no.)	1.1 ± 1.0	1.0 ± 0.9

Table 2. Ten-Year Changes in Dynamic Muscle Strength of the Knee and Elbow Extensor and Flexor Muscles

Parameter	Strength		Absolute Change (N m)	Significance			% Changes/Decade
	Baseline (N m)	Follow-Up (N m)		Time	Sex	Interaction	
Knee Extensors							
Women	98 ± 20	87 ± 21	-11 ± 15	.001	.001	.001	-11.8 ± 15.5* [†]
Men	160 ± 29	136 ± 31	-24 ± 25				-14.5 ± 15.6
Knee Flexors							
Women	54 ± 10	45 ± 12	-9 ± 8	.001	.001	.046	-17.4 ± 16.1
Men	92 ± 21	78 ± 23	-14 ± 19				-14.6 ± 18.2
Elbow Extensors							
Women	27 ± 9	25 ± 8	-2 ± 8	.001	.001	.006	-2.4 ± 32.9 [‡]
Men	45 ± 12	39 ± 11	-6 ± 9				-12.1 ± 19.3
Elbow Flexors							
Women	22 ± 7	22 ± 7	-0.3 ± 7	.001	.001	.001	2.0 ± 33.8 [‡]
Men	45 ± 10	40 ± 10	-5 ± 8				-10.2 ± 17.6

*Women, knee extensors < knee flexors; $p < .01$.

[†]Women, knee extensors > elbow flexors; $p < .0001$.

[‡]Different from men; $p < .05$.

rates of loss in both muscle groups. A histogram of the percent strength change for each muscle group is shown in Figure 1. Depending on muscle group and gender, 7–32% of subjects showed gains in muscle strength over the follow-up period.

Comparison of Cross-Sectional to Longitudinal Changes in Muscle Strength

Longitudinal changes in strength (change in strength divided by change in age) differed from cross-sectional estimations, depending on gender and muscle group (Table 3). In men, longitudinally measured strength declines in the knee extensors and flexors were ~60% greater than those observed in cross-sectional analysis ($p < .05$). Longitudinal and cross-sectional estimates of knee strength change were not different in women. No difference between cross-sectional and longitudinal analyses for elbow extensors and flexors in men or women was observed.

Muscle Mass and Body Weight Changes

Mean body weight was unchanged over the follow-up period (men, -0.1 ± 4.1 kg; women, $+1.1 \pm 5.5$ kg); however, individual weight changes ranged from a 9.9-kg loss to a 19.4-kg weight gain. Muscle mass decreased significantly over time in men and women ($p < .05$). However, percent changes in muscle mass were greater ($p < .03$) in men ($-12.9 \pm 15.5\%$ per decade) than in women ($-5.3 \pm 18.2\%$ per decade).

Physical Activity

At baseline, 28% of the cohort reported an expenditure of less than 500 kcal/wk in sports or recreational activities (5% of the cohort reported no activities). At follow-up, 33% of individuals reported an expenditure of less than 500 kcal/wk in the previous 12 months (10% of the cohort reported no activities). At the baseline evaluation, 8% of the subjects reported doing strengthening exercises regularly (>40 wk/y). This increased to 18% at follow-up. Individuals who strength trained reported higher ($p < .02$) overall levels of physical activity at the baseline and follow-up assessments than those who did not. At baseline, the quartile cutoffs for en-

ergy expenditure in sports and recreational activities for men were 392, 1355, and 2850 kcal/wk (range: 0–8953) and for women were 440, 852, and 1463 kcal/wk (range: 0–5208). Men reported higher baseline energy expenditures than women ($p < .02$), and they also demonstrated a greater decline ($p < .002$) over the follow-up period than women.

Medication Use and Chronic Diseases

The prevalence of major chronic disease categories at baseline and follow-up is presented in Table 4. The number of self-reported chronic diseases increased ($p < .001$) in both men (1.0 ± 0.9 to 1.8 ± 1.3) and women (1.1 ± 1.0 to 1.6 ± 1.2). At follow-up, men reported at least twice the prevalence of cardiac, peripheral vascular, and neurologic diseases; diabetes; and cancer compared with women. Women reported a higher incidence for osteoarthritis and musculoskeletal and respiratory problems. The number of medications used on a regular basis also increased in men (0.3 ± 0.5 to 1.5 ± 1.4) and women (0.4 ± 0.7 to 1.7 ± 1.5) over the follow-up period ($p < .001$).

Factors Related to Strength Changes Over Time

Baseline levels of muscle mass, body weight, medication use, number of chronic diseases, or physical activity were not related to change in strength of any muscle group. Table 5 contains regression coefficients for percent changes in muscle strength, regressed in separate models, on age, percent change in body weight and muscle mass, and absolute change in medication use. Age was inversely related ($p < .02$) to changes in knee extensor (equal to $-0.042 \pm 0.018\%$ per year + 1.50; see Figure 2) and knee flexor (equal to $-0.093 \pm 0.018\%$ per year + 4.50) strength but not to changes in elbow extensor and flexor strength in men and women.

Changes in other subject characteristics over time were variably associated with changes in muscle strength (Table 5). Change in strength of all muscle groups was predicted by body weight changes, with no significant differences between men and women. Changes in muscle mass were positively related to knee extensor ($p < .057$) and flexor strength ($p < .047$) changes and explained 5% of the

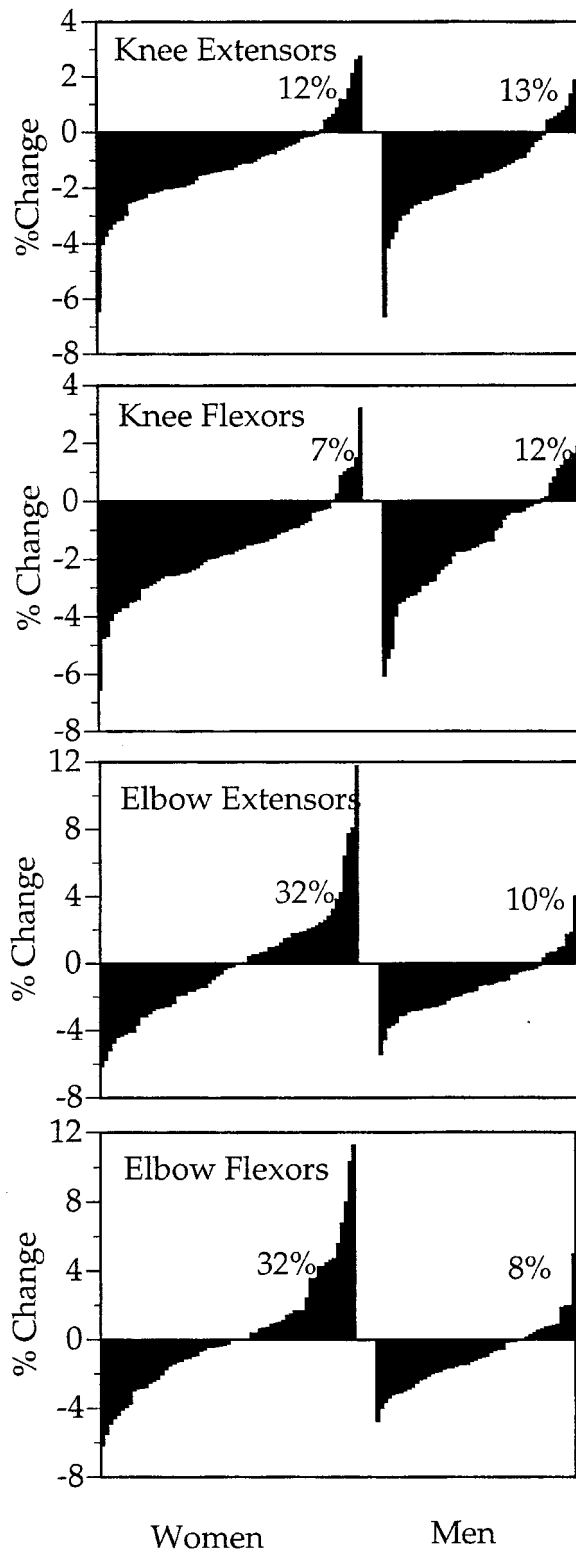


Figure 1. Histograms showing annualized changes in muscle strength in the four muscle groups tested. Women and men are on the left and right sides, respectively. Percentages are indicated for numbers of subjects not decreasing in strength over the follow-up period; 7–13% of men and women had positive changes in knee extensor and flexor strength. Approximately 32% of women and 9% of men showed an increase in elbow extensor or flexor strength.

Table 3. Cross-sectional and Longitudinal Analyses of Knee and Elbow Extensor and Flexor Isokinetic Strength

Parameter	Cross-Sectional Anal., Slope* (N m/y)		Longitudinal Anal., Change (N m/y)	
	Men	Women	Men	Women
Knee extensors	-1.48 ± 0.48	-1.01 ± 0.31	$-2.41 \pm 2.61^{\dagger}$	-1.21 ± 1.66
Knee flexors	-0.87 ± 0.36	-0.38 ± 0.16	$-1.37 \pm 1.74^{\dagger}$	-0.93 ± 0.86
Elbow extensors	-0.53 ± 0.21	-0.22 ± 0.15	-0.63 ± 0.98	-0.20 ± 0.88
Elbow flexors	-0.44 ± 0.16	-0.29 ± 0.11	-0.51 ± 0.86	-0.05 ± 0.78

*Cross-sectional analysis at baseline.

[†]Different from cross-sectional analysis; $p < .05$.

change in strength. Age was an independent predictor of changes in knee extensor ($p < .058$) or flexor strength ($p < .001$) in a regression model that included changes in muscle mass. Figure 3 shows the relationship between change in knee extensor strength and the change in body weight and muscle mass. An increase in medication usage was significantly related to a greater decline in the strength of the knee extensors and flexors in men only (Gender \times Medication use interaction; $p < .05$). Individuals who decreased their physical activity over the follow-up period had similar strength changes to those individuals who did not change their physical activity patterns or who increased their activity levels. After age, gender, and length of follow-up were controlled for, subjects reporting regular resistance-type exercise at baseline and follow-up or at follow-up only did not have strength changes (absolute or percent change) different from those not doing this type of exercise.

DISCUSSION

To our knowledge, this is the first investigation to report longitudinal changes in dynamic strength in major muscle groups of the arm and leg in a large sample of older men and women. The 64% response rate for this study is the highest reported for follow-up studies of lower body strength. This is also the first study to report longitudinal changes in muscle mass, physical activity, and health status in relation to changes in muscle strength in the same cohort.

Table 4. Prevalence of Chronic Diseases at Baseline and Follow-Up

	Baseline (%)		Follow-Up (%)	
	Men	Women	Men	Women
Cardiac	10	1	29	9
Peripheral vascular	5	6	12	6
Cerebrovascular	0	0	4	3
Hypertension	6	4	17	16
Neurologic	6	4	13	7
Osteoarthritis	25	35	29	46
Musculoskeletal	15	29	19	29
Diabetes	2	1	8	1
Cancer	6	1	8	4
Gastrointestinal	19	9	12	9
Respiratory	2	10	4	12
Psychiatric	0	4	4	6
Osteoporosis	0	0	2	4

Table 5. Regression Coefficients for Factors Associated With % Change in Muscle Strength/Decade

Factor	Muscle Group	Men	Women	Factor	Significance	
					Gender Eff.	Interact.
Age	KE	-0.417	-0.503	0.013	NS	NS
	KF	-0.932	-1.084	0.000	NS	NS
	EE	-0.175	-0.304	NS	NS	NS
	EF	+0.098	-0.024	NS	0.02	NS
% Change, body weight	KE	0.80	0.67	0.000	NS	NS
	KF	0.40	0.53	0.016	NS	NS
	EE	0.83	0.95	0.006	NS	NS
	EF	0.76	0.71	0.035	0.037	NS
% Change, muscle mass	KE	0.01	0.29	0.057	NS	NS
	KF	0.10	0.29	0.047	NS	NS
	EE	-0.11	0.37	NS	NS	NS
	EF	-0.05	0.26	NS	NS	NS
Change in med. use	KE	-3.72	0.33	NS	NS	0.044
	KF	-4.44	0.60	NS	NS	0.021
	EE	-1.13	2.24	NS	0.043	NS
	EF	-2.06	2.01	NS	0.021	NS

Note: KE = knee extensors; KF = knee flexors; EE = elbow extensors; EF = elbow flexors; NS = not significant.

These results confirm the overall decline in muscle strength in older men and women, and they demonstrate that longitudinal changes in dynamic muscle strength for lower extremity muscles can be as much as 60% greater than that measured in a cross-sectional analysis. These results also indicate that the decline in strength is not inevitable. Muscle strength change was influenced by the magnitude and direction of

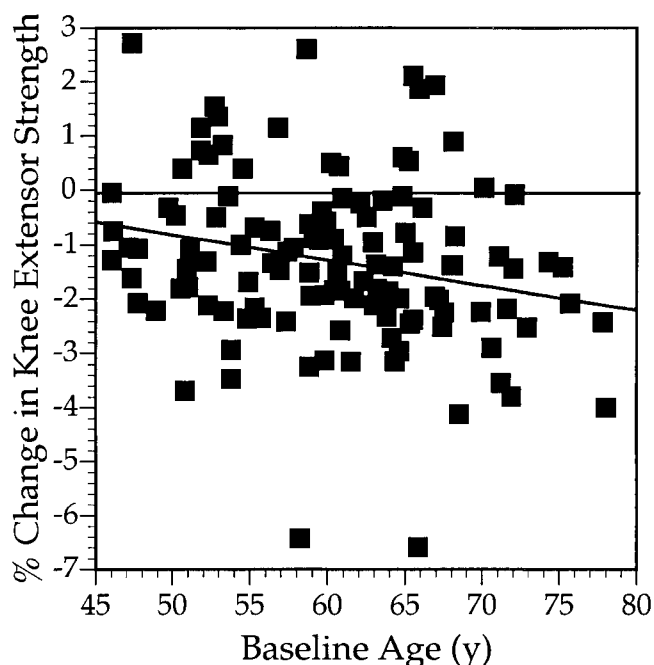


Figure 2. Plot showing the relationship between the percent decline in knee extensor strength in men and women by baseline age. The equation that describes this relationship is % decline = $(-0.042 \pm 0.018 \times \text{baseline age}) + 1.50$; $p < .02$.

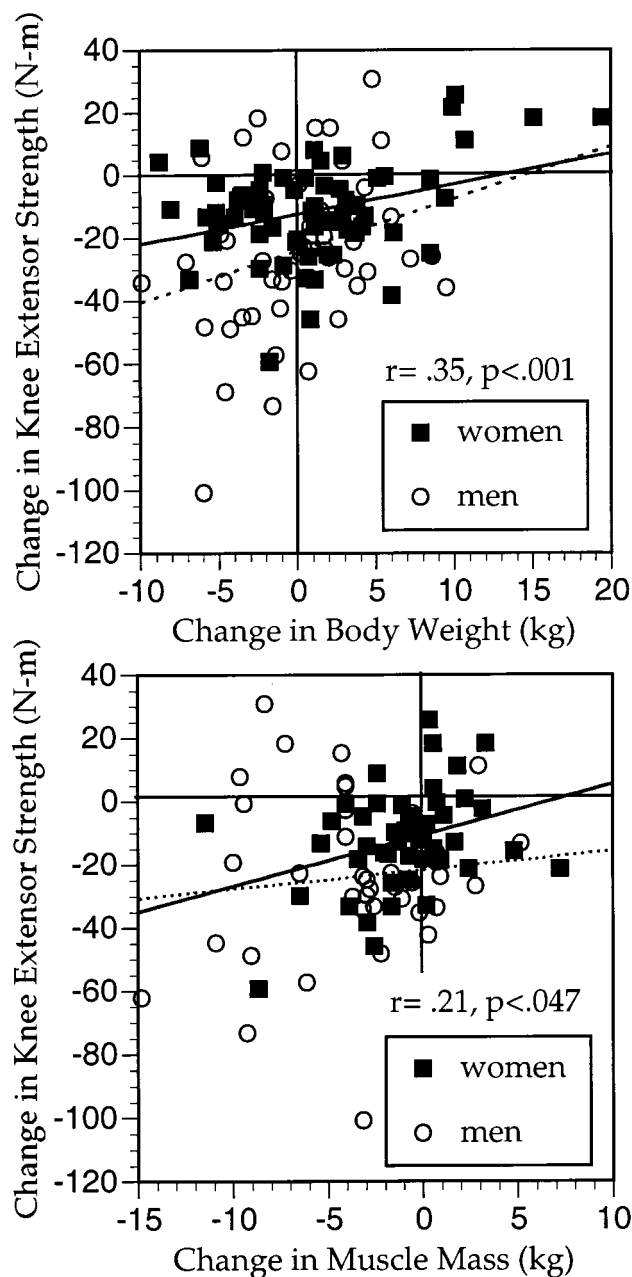


Figure 3. Two scatter plots showing the relationship between the absolute change in knee extensor muscle strength (deg/s) vs the absolute change in body weight or the absolute change in muscle mass. Women are represented by filled squares and solid curves; men are represented by open circle and dashed curves. The correlation coefficients for men and women combined are represented because there was no gender effect or significant interaction term.

the body weight and muscle mass change. However, baseline or change in physical activity patterns were not associated with the changes we observed in muscle strength.

Lower and Upper Extremity Muscle Strength Changes

The rates of loss in knee extensor and flexor muscle strength we observed in men and women are lower than those in men reported by Aniansson and coworkers, the only other

group to report on longitudinal changes in isokinetic strength (13). They reported 35% loss in knee extensors and a 4.2% loss in body weight over 11 years in men initially aged 69 years. The smaller rates of decline found in our study may reflect the relatively young age of this cohort, and the finding supports other analyses that suggest that the change is a function of age (6,26,27). Maintenance of body weight in our subjects may also have contributed to the smaller rates of decline observed. Preservation of grip strength has been observed in men who maintained or increased body weight over 27 years, although it is not known if this was mediated by the maintenance of muscle mass (15).

A few investigations have addressed longitudinal changes in upper body strength measures other than grip strength, and those studies have only assessed isometric strength (6,9,10). Annualized estimates of isometric strength loss in the elbow extensors and flexors ranged from 1.4% to 6.8%, with no reported difference between these muscles groups or gender (10). We also demonstrated no difference in strength loss between the elbow extensor and flexor muscle groups. In contrast to previous studies demonstrating similar isometric strength losses between genders, in the present study women demonstrated significantly lower rates of change in dynamic muscle strength of the elbow extensors and flexors compared with men. Muscle distribution differs between men and women such that women have a smaller percentage of muscle in their arms (28); therefore, they have less to lose and the potential to gain more muscle.

Our results suggest that there is variability in the response to aging by different muscles groups, particularly in women. The decline in the strength of the elbow extensors and flexors was smaller than that of knee extensors or flexors in women, supporting the findings of Lynch and coworkers (4). In contrast, Rantanen and coworkers found a decline in isometric elbow flexion strength over 5 years with no change in knee extension strength (9). This maintenance of knee strength with aging is a unique finding and may be related to the relatively short follow-up in that study or the exclusion of subjects with chronic medical conditions from the follow-up assessment. Clearly, a more specific assessment of the relative changes in upper versus lower extremity muscle groups is required in order to more clearly define the therapies best suited for maintenance of function in different muscle groups.

Strength gains were also observed for some individuals in all muscle groups tested. Depending on muscle group, 7–32% of our subjects showed positive changes over the follow-up period. This pattern of change is also reported in other studies, in which up to 30% of the population has shown an increase in strength over extended follow-up periods (8,9,26,29). This points to the potential to modify muscle strength by exercise, accretion of lean mass, or perhaps improved nutrition over a decade in a population of older adults in whom strength is expected to decline.

Muscle Strength and Muscle Mass

The total amount of muscle is a major determinant of the force-generating capacity of the muscle, as demonstrated by the high correlation between muscle mass and strength in a cross-sectional analysis (4). This has led some to conclude

that the loss in muscle strength is due entirely to the loss in muscle mass (30). However, a significant association between *the change* in muscle strength and mass with exercise training or restricted activity is rarely observed (31,32). This, along with the finding of disproportionately greater loss of strength compared to lean tissue declines over 11 to 15 years and no correlation between muscle strength and fiber area changes (7,10), suggests that other neuromuscular changes may mediate muscle strength change. In our cohort, muscle mass changes explained a small (5%) part of the variance in knee strength. In a recent publication we reported that the change in area of the quadriceps muscle over 12 years was a significant contributor to the loss of knee extension strength in a small group of elderly men (33). However, not all studies have found a significant relationship between the changes in these two variables with normal aging (8).

Limitations of the use of isokinetic devices has been reported; however, the same instrument and protocol was used at both evaluations. The use of various methods to estimate muscle mass or strength in longitudinal studies may affect the estimates of the contribution of muscle mass changes on strength changes. Our analysis is limited by the use of one 24-hour urine creatinine collection to estimate whole body muscle mass, by predictions of regional strength changes with whole body muscle mass estimates, and by the relatively low precision of the creatinine method. Regardless of this, we have demonstrated that muscle mass change has a significant impact on the functional characteristics of the muscle. However, in addition to methodological limitations, the magnitude of this impact may also be dependent on the age, health, specific activities, and length of follow-up of the populations studied.

Although individuals who maintained or gained muscle mass had smaller losses or even gains in strength, there were some individuals who lost strength in spite of muscle mass maintenance or gains. This emphasizes the importance of other factors as significant mediators in the declines in muscle strength. Indeed, age was a significant independent predictor of strength changes after adjusting for muscle mass, indicating the importance of other unmeasured age-related factors on the decline in maximal force production we observed.

Physical Activity and Muscle Strength

Cross-sectional studies of healthy older subjects have reported that the time spent in leisure time physical activity was related to knee extensor muscle strength (10,34). In a longitudinal analysis, Rantanen and coworkers demonstrated that maintaining or increasing activity levels prevented or attenuated the strength declines with age (9). However, changes in muscle strength and physical activity were not significantly associated in our cohort. These different findings may be a result of cohort differences or of different methods of strength and physical activity assessment. Furthermore, relative to other estimates in the United States (35), a low percentage of our population reported being sedentary, and on average they had relatively high weekly energy expenditure rates. Therefore, our population may be above a threshold where physical activity levels have a direct effect on muscle strength. Additionally, our subjects

were followed for 10 years and the questionnaire only addressed the past year's physical activity recall. Physical activity and lifestyle habits practiced over a lifetime may have a stronger physiological impact than more recent events (36,37). Our assessment of physical activity was did not query type or intensity of activities specific to the muscle groups tested. Bassey and coworkers found that a change in the use of the hands was related to the change in grip strength (26), which highlights the task-specific relationships. Future studies should identify specific habitual activities that affect individual muscle groups in order to impart understanding of the effect of activity on muscle strength. Finally, changes in muscle strength may be mediated through a host of mechanisms not tested in this study, including modulation of contractile characteristics, motor unit function, fiber type or metabolic parameters, all of which may be influenced by physical activity.

Health Status and Muscle Strength

Representation of mostly healthy subjects in a cross-sectional or longitudinal analysis may lead to an underestimation of the true muscle strength changes in the general population. In fact, the exclusion of subjects with some chronic conditions may explain why no knee extensor strength deficits occurred over 5 years in one longitudinal study (9). Possible selection bias is most crucial in the older age groups, in which the healthy "survivors" are more likely to participate in studies. In the current study, chronic medical conditions reported were of sufficient diversity, prevalence, and incidence to represent a broad spectrum of the aging population. Two longitudinal studies of grip strength have reported a greater rate of decline than that observed in the same population in cross-sectional analyses (26,27). The current study is the first to confirm that this is also true for dynamic strength of the knee extensors and flexors in men and that the strength declines may be as much as 60% greater than those from a cross-sectional analysis. Additionally, individuals who did not return for follow-up in our study were initially older and weaker, and therefore would have been expected to have greater rates of strength loss over time. Therefore, we may be underestimating the changes in strength in this cohort.

Our data also suggest that change in medication usage, perhaps serving as a more specific proxy for an increased prevalence of comorbid conditions, may influence the strength changes observed in men, because this variable was related to the change in knee extensors, the largest muscle group tested. The development of chronic medical conditions and intrinsic changes occurring within the neuromuscular system over time may have mediated changes in strength by means of other mechanisms known to be important determinants of strength.

Conclusions

The results of this study quantify the substantial longitudinal decline in maximal dynamic force production of upper and lower extremity muscle groups. Although strength is expected to decline in these older subjects, many individuals increased strength over the follow-up period, pointing to the potential to modify muscle function by exercise or

through accretion of lean tissue with age. Older subjects in general had greater relative losses in leg strength than younger subjects in our cohort. Muscle mass changes accounted for 5% of the change in strength. In men, a change in health status predicted muscle strength declines. Because only a small amount of the variance in strength was explained by muscle mass loss and because of the lack of association with physical activity, there is a need to explore the relative contribution of other cellular, neural, or metabolic mediators of changes in muscle function.

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Editor Nominations

Journal of Gerontology: Biological Sciences

The Gerontological Society of America's Publications Committee is seeking nominations for the position of Editor of the *Journal of Gerontology: Biological Sciences*.

The position will become effective January 1, 2002. The Editor makes appointments to the journal's editorial board and develops policies in accordance with the scope statement prepared by the Publications Committee and approved by Council (see the journal's masthead page). The Editor works with reviewers and has the final responsibility for the acceptance of articles for his/her journal. The editorship is a voluntary position. Candidates must be dedicated to developing a premier scientific journal.

Nominations and applications may be made by self or others, but must be accompanied by the candidate's curriculum vitae and a statement of willingness to accept the position. **All nominations and applications must be received by May 1, 2001.** Nominations and applications should be sent to the GSA Publications Committee, Attn: Jennifer Campi, The Gerontological Society of America, 1030 15th Street, NW, Suite 250, Washington, DC 20005-1503.