Journal of Gerontology: MEDICAL SCIENCES
2006, Vol. 61A, No. 10, 1059–1064

The Loss of Skeletal Muscle Strength, Mass, and Quality in Older Adults: The Health, Aging and Body Composition Study

Bret H. Goodpaster,[1] Seok Won Park,[2] Tamara B. Harris,[3] Steven B. Kritchevsky,[4] Michael Nevitt,[5] Ann V. Schwartz,[5] Eleanor M. Simonsick,[6] Frances A. Tylavsky,[7] Marjolein Visser,[8] and Anne B. Newman,[1,2] for the Health ABC Study

Departments of [1]Medicine and [2]Epidemiology, University of Pittsburgh, Pennsylvania.
[3]Laboratory for Epidemiology, Demography and Biometry, National Institute on Aging, Bethesda, Maryland.
[4]The Sticht Center on Aging, Department of Internal Medicine, Wake Forest University School of Medicine, Winston-Salem, North Carolina.
[5]Department of Epidemiology and Biostatistics, University of California, San Francisco.
[6]Clinical Research Branch, National Institute on Aging, Baltimore, Maryland.
[7]Department of Preventive Medicine, University of Tennessee, Memphis.
[8]Institute for Research in Extramural Medicine, Vrije Universiteit, Amsterdam, The Netherlands.

Background. The loss of muscle mass is considered to be a major determinant of strength loss in aging. However, large-scale longitudinal studies examining the association between the loss of mass and strength in older adults are lacking.

Methods. Three-year changes in muscle mass and strength were determined in 1880 older adults in the Health, Aging and Body Composition Study. Knee extensor strength was measured by isokinetic dynamometry. Whole body and appendicular lean and fat mass were assessed by dual-energy x-ray absorptiometry and computed tomography.

Results. Both men and women lost strength, with men losing almost twice as much strength as women. Blacks lost about 28% more strength than did whites. Annualized rates of leg strength decline (3.4% in white men, 4.1% in black men, 2.6% in white women, and 3.0% in black women) were about three times greater than the rates of loss of leg lean mass (~1% per year). The loss of lean mass, as well as higher baseline strength, lower baseline leg lean mass, and older age, was independently associated with strength decline in both men and women. However, gain of lean mass was not accompanied by strength maintenance or gain (ß coefficients; men, –0.48 ± 4.61, $p = .92$, women, –1.68 ± 3.57, $p = .64$).

Conclusions. Although the loss of muscle mass is associated with the decline in strength in older adults, this strength decline is much more rapid than the concomitant loss of muscle mass, suggesting a decline in muscle quality. Moreover, maintaining or gaining muscle mass does not prevent aging-associated declines in muscle strength.

MUSCLE weakness is consistently reported as an independent risk factor for high mortality in older adults (1–5). Since muscle strength also appears to be a critical component in maintaining physical function, mobility, and vitality in old age, it is paramount to identify factors that contribute to the loss of strength in elderly persons. Sarcopenia, the age-associated loss of skeletal muscle mass (6–10), has been postulated to be a major factor in the strength decline with aging (9–11). Moreover, sarcopenia is related to functional impairment (12,13), disability (14,15), falls (16), and loss of independence (17) in older adults. However, the prospective association between changes in muscle mass and changes in strength has not been extensively evaluated in older adults. By using modern imaging methods such as dual-energy x-ray absorptiometry (DXA) and computed tomography (CT), we can precisely measure the quantity and composition of muscle and detect small changes over time (18–20). We can thereby help elucidate whether the loss of strength depends primarily on the loss of muscle mass, or whether there is actually a loss of muscle *quality*, that is, a loss of strength per unit muscle mass.

The Health, Aging and Body Composition (Health ABC) study was designed to prospectively determine the role of longitudinal changes in body composition in the risk of incident functional limitations in well-functioning community-dwelling older adults. This study aims to: (i) describe the change in muscle strength, mass, and quality over 3 years; and (ii) determine whether change in total and appendicular lean mass as well as body weight are related to change in muscle strength of older adults.

Methods

Population

The Health ABC study cohort consisted of a volunteer sample of 3075 men (48.4%) and women (51.6%) aged 70–79 years, of whom 41.6% are African American. Participants were recruited from Medicare listings in Pittsburgh, Pennsylvania and Memphis, Tennessee. Eligibility criteria included self-report of no difficulty walking one quarter of a mile or climbing 10 steps, and no difficult with basic activities of daily living. All participants gave informed consent, and each participating institution's human subject review board approved the protocol. For the present anal-

Table 1. Baseline Characteristics of the Participants

Baseline Variable	White Men $N = 634$	Black Men $N = 295$	All Men $N = 929$	White Women $N = 567$	Black Women $N = 384$	All Women $N = 951$	Total $N = 1880$
Age	73.7 ± 2.8	73.4 ± 2.8	73.6 ± 2.8	73.4 ± 2.8	73.0 ± 2.8	73.2 ± 2.8	73.5 ± 2.8
Height, cm	173.6 ± 6.1	173.2 ± 6.8	173.5 ± 6.3*	159.7 ± 5.8	160.0 ± 6.4	159.8 ± 6.1*	166.6 ± 9.2
Weight, kg	81.6 ± 12.1	82.0 ± 14.4	81.7 ± 12.9*,†	65.7 ± 11.8	75.6 ± 14.6	69.7 ± 13.9*,†	75.6 ± 14.7
BMI, kg/m^2	27.0 ± 3.6	27.3 ± 4.2	27.1 ± 3.8†	25.7 ± 4.3	29.5 ± 5.4	27.3 ± 5.1†	27.2 ± 4.5
Total % fat	28.8 ± 4.6	27.1 ± 5.1	28.2 ± 4.8*	38.9 ± 5.5	40.2 ± 5.6	39.4 ± 5.6*	33.9 ± 7.7
Total fat, kg	23.8 ± 6.6	22.6 ± 7.4	23.4 ± 6.9*,†	26.1 ± 7.6	31.0 ± 9.3	28.0 ± 8.7*,†	25.8 ± 8.2
Leg torque, Nm	133.4 ± 30.0	140.4 ± 35.8	135.6 ± 32.1*,†	79.5 ± 19.8	88.4 ± 23.7	83.1 ± 21.9*,†	109.0 ± 38.0
Leg lean mass, kg	8.65 ± 1.20	9.26 ± 1.44	8.84 ± 1.31*,†	5.89 ± 0.94	7.03 ± 1.24	6.35 ± 1.21*,†	7.58 ± 1.77
Specific torque, Nm/kg	15.46 ± 2.95	15.22 ± 3.39	15.39 ± 3.10*,†	13.52 ± 2.89	12.76 ± 3.32	13.21 ± 3.09*,†	14.29 ± 3.28

Notes: Data shown as mean ± standard deviation.
*Gender difference at $p < .01$.
†Racial difference within gender at $p < .01$.
BMI = body mass index.

ysis, only persons with complete data for isokinetic knee extensor strength and DXA measurements of body composition at both baseline and 3-year follow-up were included ($n = 1880$). At baseline, 392 individuals (12.7%) were excluded from the strength test due to uncontrolled hypertension, stroke, bilateral knee replacement, or severe bilateral knee pain. Among the remaining 2683 participants, 151 (5.6%) had died, 90 (3.4%) were lost to follow-up, and 312 (11.6%) could not visit clinic due to illness, immobility, or institutionalization. At follow-up, 9.3% of the 2130 participants were not eligible due to strength test contraindications listed above. Finally, 51 participants (2.4%) with missing data on body composition measurements were excluded from the analyses.

Body Composition

Total body and leg lean mass were assessed using DXA (Hologic QDR 4500, software version 8.21; Bedford, MA). The ability to measure small (~1%) changes in leg lean mass with DXA is quite good (21). Bone mineral content was subtracted from the total and regional lean mass to define total nonbone lean mass, which represents primarily skeletal muscle in the extremities (22). Total body fat mass and percent body fat was also measured. Thigh muscle cross-sectional area was measured at baseline by using CT. Muscle attenuation values were also measured as a marker of muscle composition (23). The test–retest variability and the interobserver variability (four image analysts blinded to image identity) for skeletal muscle area are both small (coefficient of variation <5%).

Strength Assessments

Isokinetic knee extensor strength was measured (Kin-Com dynamometer, 125 AP; Chattanooga, TN) as described previously (20). The interexaminer, intrasubject, and combined coefficients of variation in strength examined in 63 participants were 4.8%, 10.7%, and 11.7%, respectively. Muscle quality (specific torque; Nm/kg) was defined as the ratio of strength (isokinetic torque in Nm) to leg lean mass (in kg) by DXA.

Other Covariates

Smoking status, physical activity (24), education, family income, and health status were considered as possible confounders of the associations between changes in body composition and changes in strength. General health status was assessed as the total number of 11 chronic health conditions, using self-report with confirmation by treatment and medications. These conditions included cancer, myocardial infarction, congestive heart failure, depression, diabetes, hypertension, knee osteoarthritis, osteoporosis, peripheral arterial disease, pulmonary disease, and gastrointestinal disease.

Analysis

The differences in strength and body composition between baseline and 36-month follow-up were assessed by paired *t* test and were expressed in both absolute (Δ; change) and proportional terms (% change). Two-way analysis of variance was used to determine gender, race, and interaction effects on the changes in muscle mass and strength. Simple correlations and multiple linear regressions were used to examine the relationship between baseline as well as changes in body composition parameters with changes in strength. The analyses were repeated within gender and adjusted for smoking status, physical activity, education, family income, and health status. All analyses were performed using SPSS (version 12.0.0; SPSS Inc., Chicago, IL) and SAS (version 8.02; SAS Institute, Inc., Cary, NC).

Results

At baseline, men were stronger than women, and within gender, blacks were stronger than whites. However, specific torque (strength per unit mass) was lower in blacks than in whites (Table 1). All race and gender groups of participants lost a significant amount of their leg lean mass and strength over 3 years (Table 2). The absolute strength decline (Δ leg torque) was almost 2-fold greater in men compared to women ($p < .001$). Within the same gender, blacks lost about 28% more strength than whites ($p = .001$). The proportional loss of strength (% Δ leg torque) was greater in men than in women, but was similar in blacks and whites. The changes in leg lean mass showed a similar pattern; men lost more leg lean mass than women, and blacks lost more leg lean mass than whites in both absolute and proportional terms.

The annualized rates for strength declines were 3.42% and 4.12% in white and black men and 2.65% and 2.97% in white and black women, respectively (Figure 1). These rates of strength declines were almost 3 times greater than the rates for loss of leg lean mass, which were about 1% per

Table 2. Changes in Muscle Strength and Body Composition During the Follow-Up Period of 3 Years by Race and Gender

Changes	White Men (N = 634)	Black Men (N = 295)	White Women (N = 567)	Black Women (N = 384)	p Value for Gender Difference	p Value for Race Difference
Δ Weight, kg	−.49 ± 3.76	−.99 ± 4.67	−.17 ± 3.48	−.66 ± 4.68	.096	.011
Δ BMI, kg/m²	.03 ± 1.30	−.13 ± 1.67	.18 ± 1.53	.05 ± 2.02	.132	.011
Δ Total % fat	.76 ± 2.09	.79 ± 2.63	.42 ± 2.17	.04 ± 2.66	<.001	.064
Δ Total fat, kg	.52 ± 2.62	.49 ± 3.00	.30 ± 2.59	−.18 ± 3.35	<.001	.067
Δ Total lean mass, kg	−.87 ± 1.96	−1.19 ± 2.30	−.31 ± 1.49	−.30 ± 1.97	<.001	.092
Δ Leg lean mass, kg	−.27 ± .47	−.37 ± .54	−.16 ± .36	−.21 ± .47	<.001	.001
% Δ Leg lean mass	−3.03 ± 5.22	−3.97 ± 5.81	−2.59 ± 5.87	−2.78 ± 6.96	.004	.048
Δ Leg torque, Nm	−15.38 ± 21.36	−19.74 ± 26.38	−7.94 ± 14.09	−10.21 ± 19.76	<.001	.001
% Δ Leg torque	−10.25 ± 17.87	−12.36 ± 22.48	−7.94 ± 22.54	−8.91 ± 27.84	.008	.153
Δ Specific torque, Nm/kg	−1.33 ± 2.46	−1.61 ± 2.90	−1.02 ± 2.46	−1.14 ± 2.77	.002	.110
% Δ Specific torque	−7.33 ± 18.43	−8.61 ± 23.27	−5.43 ± 22.38	−6.04 ± 29.77	.108	.405

Notes: Data shown as mean ± standard deviation; Difference; Baseline − 36 month; *p* values; 2-way analysis of variance.
BMI = body mass index.

year throughout gender and race. The specific torque was also decreased in men and women, ranging from –5.43% to –8.61% over 3 years across groups (Table 2). However, there were no gender or racial differences in the proportional changes of specific torque (% Δ specific torque), suggesting that the loss of strength was similar across gender and race after controlling for the loss of lean mass.

Baseline weight and measures of muscle mass, including total lean mass, leg regional lean mass, and thigh muscle cross-sectional area, were significantly correlated to changes in strength (Table 3). However, baseline measures of fat mass, including total body percent fat, total fat mass, leg regional fat mass, and muscle attenuation as a marker of muscle fat content, were not associated with changes in strength. Strength declines were greater among participants with higher initial strength (Table 3), although the changes in lean mass were similar between quartiles of baseline strength (Figure 2).

The bivariate correlations between changes in body composition parameters and changes in strength are also summarized in Table 3. Absolute and relative changes of weight (Δ weight and % Δ weight) were significantly associated with strength decline in both men and women ($p < .001$). The changes in total and leg lean mass were significantly associated with changes in strength. However, the changes in total and leg fat mass were generally not associated with changes in strength. Men and women who lost more than 3% of their body weight over the 3 years ($N = 263$ for men and $N = 270$ for women) lost significantly more leg lean mass and strength than did those who either maintained ($N = 492$ for men and $N = 457$ for women) or gained ($N = 174$ for men and $N = 224$ for women) weight (Figure 3). However, participants who gained weight had no advantage over participants who were weight stable in either preventing or attenuating the strength decline, despite slight increases in their leg lean mass.

As shown in Table 4, for all men and all women, higher baseline strength, lower baseline leg lean mass, greater loss of leg lean mass, and increasing age were associated with greater strength decline. However, baseline leg lean mass and changes in leg lean mass together explained only about 5% of the changes in strength over 3 years in both men and women. The results were further stratified by the direction of lean mass change (loss or gain of leg lean mass) because the

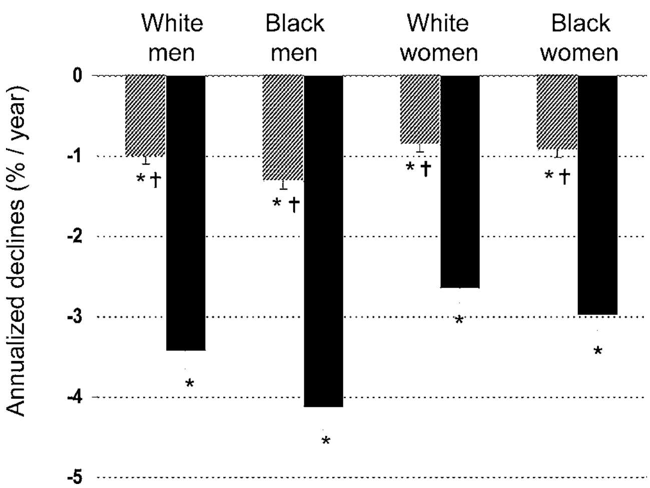

Figure 1. Annualized rates for declines in leg lean mass (*hatched bar*) and muscle strength (*black bar*) by gender and race. Gender difference within race, $p < .01$. Racial difference within gender, $p < .05$.

Table 3. Bivariate Correlations Between Various Body Composition Parameters and Changes in Strength

	Men	Women
Baseline Values		
Initial strength	−0.402*	−0.426*
Weight, kg	−0.089*	−0.037
Total % fat	0.065	0.038
Total fat, kg	−0.006	−0.010
Leg fat mass, kg	0.007	0.006
Total lean mass, kg	−0.131*	−0.076†
Leg lean mass, kg	−0.136*	−0.101*
Muscle area, cm²	−0.148*	−0.078†
Muscle attenuation, HU	0.041	−0.030
Changes over 3 y		
Δ Weight, kg	0.116*	0.138*
Δ Weight, %	0.124*	0.140*
Δ Total fat %	0.012	0.057
Δ Total fat, kg	0.036	0.111*
Δ Leg fat mass, kg	0.047	0.093*
Δ Total lean mass, kg	0.183*	0.149*
Δ Leg lean mass, kg	0.171*	0.176*

Notes: *$p < .01$.
†$p < .05$.
HU = Hounsfield Units; Δ = change.

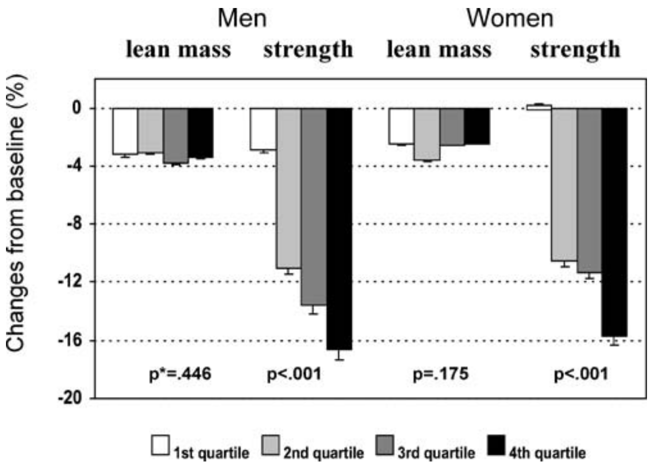

Figure 2. Declines in leg lean mass and muscle strength over 3 years by quartiles of baseline strength, stratified by gender. Values of p, analysis of variance between quartiles within the same gender.

association of Δ lean mass and Δ strength appeared to be nonlinear. Strength declined as a function of lean mass in participants who lost their lean mass, but there was no association between Δ lean mass and Δ strength in participants who gained lean mass (Table 4). Therefore, there was no gain in strength in participants who gained weight or lean mass. These associations remained after controlling for weight and weight loss and further adjusting for potential confounders including smoking status, physical activity, education, family income, and health status.

Discussion

A primary finding of this study was that initially well-functioning older men and women exhibited a 3-fold greater loss in strength than decline in muscle mass over the course of 3 years of follow-up. This pattern was consistent for men and women and for blacks and whites. Another novel finding was that maintenance or even gain of lean mass in these older men and women did not necessarily prevent the loss of strength. Thus, while these data do not diminish the importance of maintaining muscle mass with old age, they do underscore the importance of muscle quality in older adults.

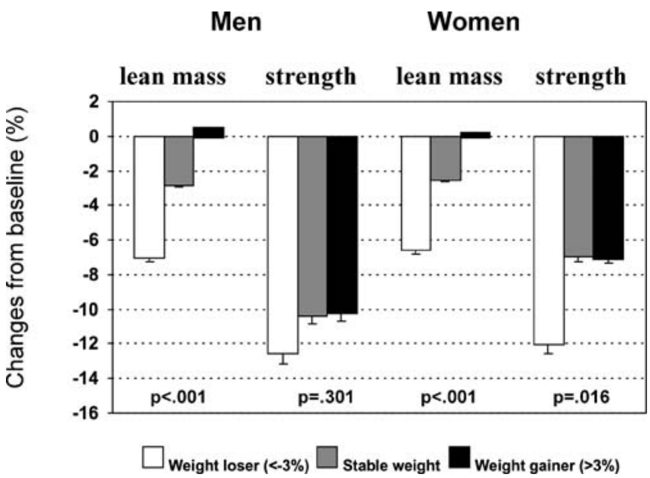

Figure 3. Declines in leg lean mass and muscle strength over 3 years by weight change groups, stratified by gender. Values of p, analysis of variance between groups within the same gender.

Table 4. Multiple Linear Regression Model to Predict Changes in Strength, Stratified by Gender

	Men		
	All Men (N = 929)	Lean Mass Losers (N = 692)	Lean Mass Gainers (N = 237)
Predictors	β ± Standard Error		
Baseline torque, Nm	−0.37 ± 0.02*	−0.40 ± 0.03*	−0.33 ± 0.05*
Baseline leg lean mass, kg	3.32 ± 0.62*	3.87 ± 0.71*	3.04 ± 1.38
Δ Leg lean mass, kg	8.31 ± 1.38*	13.07 ± 2.08*	−0.48 ± 4.61
Age, y	−0.64 ± 0.24*	−0.58 ± 0.28*	−0.77 ± 0.49
Race	−3.16 ± 1.47	−2.84 ± 1.65	−3.46 ± 3.19
R^2 (total variance explained by the model)	0.23	0.26	0.14
	Women		
	All Women (N = 951)	Lean Mass Losers (N = 654)	Lean Mass Gainers (N = 297)
Predictors	β ± Standard Error		
Baseline torque, Nm	−0.40 ± 0.02*	−0.43 ± 0.03*	−0.34 ± 0.05*
Baseline leg lean mass, kg	2.68 ± 0.50*	2.50 ± 0.60*	3.73 ± 0.94*
Δ Leg lean mass, kg	8.29 ± 1.20*	10.42 ± 2.02*	−1.68 ± 3.57
Age, y	−0.51 ± 0.17*	−0.69 ± 0.21*	−0.02 ± 0.31
Race	−1.48 ± 1.09	−0.81 ± 1.34	−1.57 ± 1.89
R^2 (total variance explained by the model)	0.24	0.26	0.16

Notes: The significant negative coefficients indicate that higher baseline strength and increasing age were associated with greater declines in strength. The significant positive coefficients indicate that higher baseline leg lean mass and smaller decline in lean mass are predictive of smaller declines in strength.

*$p < .01$.

The annualized rates of strength decline (3.6% in men and 2.8% in women) in these relatively healthy older adults were higher than the typical 0.8%–2.0% per year previously reported in either cross-sectional studies or in longitudinal investigations of relatively younger individuals (25–31). However, our data are supported by observations that the age-associated loss of strength is usually more pronounced at more advanced ages (25,26,30,31). It is likely that previous cross-sectional studies underestimated the true age-related decreases in strength. Indeed, in cross-sectional studies of this Health ABC study cohort at baseline, leg strength was approximately 2% lower per year of increasing age in both men and women (11). The current longitudinal study eliminates much of the survival effect bias that is likely in cross-sectional studies, such that stronger persons may have had a better chance to survive to old age and to be examined in baseline cross-sectional comparisons.

Greater strength decline in these men and women was associated with both lower initial leg lean mass and greater loss of leg lean mass. Interestingly, men lost more strength than women even after accounting for their greater initial strength. There was no racial difference in the proportionate loss of strength. The Baltimore Longitudinal Study on Aging (7,8,26,30) reported that men had greater rates of strength decline than women, and that increasing age was associated with greater loss of strength. Hughes and colleagues (29) demonstrated that older age, greater proportionate loss of body weight and muscle mass, and change in medication use were related to the loss of strength over time, but they did not include baseline strength in the prediction model. In accord with our results, Frontera and colleagues (27) reported that muscle strength at baseline and changes in muscle cross-sectional area were independent correlates of strength decline over 12 years. Taken together, these studies suggest that preserving lean mass would indeed help attenuate the strength decline with age.

Although it has been postulated that reduced muscle mass plays a major role in the age-related decline of strength (9,32,33), in this large cohort of older adults, initial lean mass and changes of lean mass could explain only a small portion (~5%) of variability of strength decline. Moreover, even individuals who maintained their lean mass became weaker, and individuals gained weight and lean mass did not become stronger as might have been expected. This finding further suggests that alterations in muscle quality play a role in the loss of strength in old age. Hughes and colleagues (29) also reported that changes in muscle mass explained only 5% of the changes in strength. Some studies have reported no age-associated changes in muscle quality (8,27,33,34), whereas others showed significant declines with age (35,36). It is likely that small sample sizes, different age ranges of participants, and different methods used to estimate muscle mass contribute to these inconsistent findings. Ours is the first large-scale study conducted specifically in older adults to examine changes in muscle quality using direct measurements of muscle mass, thereby addressing many of these previous limitations.

There are additional interpretations of the association between age-related loss of muscle mass and strength. It is possible that muscle weakness leads to decreased function, diminished physical activity, and sometimes immobility, consequently leading to secondary muscular disuse atrophy. Thus, decreased muscle mass is likely both the result and the cause of the age-related loss of strength. Both the selective loss of type 2 muscle fibers (37) and increased levels of proinflammatory cytokines (38) have been postulated to be related to the loss of strength with aging. Moreover, exercise-induced increases in strength are typically greater than would be expected for the concomitant increase in muscle mass (39), although this dissociation between changes in strength and mass has recently been challenged in studies examining changes in both the strength and size of single muscle cells (40). Thus, it is possible that age-related neurological changes, the hormonal and metabolic milieu, pro-inflammatory cytokines, and perhaps fat infiltration—lipotoxicity—may contribute to progressive muscle weakness in older adults. Further studies are needed to help elucidate how these factors may be related to changes in muscle mass and strength with aging.

Those who were stronger at baseline were more likely to lose more strength, such that baseline strength accounted for approximately 18% of the subsequent loss of strength after adjusting for age, race, and gender. This negative association was consistent whether strength change data were expressed in absolute or proportionate changes (data not shown) and was observed for men and women and for blacks and whites. These results may lead to the interpretation that the loss of strength is inevitable, and may even be greater in the strongest individuals. However, further analyses of participants who were excluded from the follow-up strength test suggest that greater strength loss in those with higher baseline strength may partly be explained by survival bias. The mortality rate in this cohort was more than 2-fold higher in the lowest quartiles of baseline strength than in the highest quartile (5). Failure to return for the follow-up clinic visit was also more common in participants in the lower quartiles of baseline strength. Participants who did not return were weaker at baseline. They were also older, more likely to be black, more obese, and had more chronic diseases. Therefore, the participants in this analysis appeared to be healthier than members of the overall Health ABC study cohort. Weaker participants who dropped out could have likely had greater strength losses, thus this selection bias may have attenuated the observed loss of strength. In addition, we cannot discount the possibility that weaker participants at baseline lost less strength simply because they regressed towards the mean.

Despite the novel findings and potentially important implications for preserving or enhancing health in old age, our study has several limitations. The Health ABC study cohort was restricted to a relatively narrow age range at baseline, and our findings should not be generalized to other age groups. In addition, this cohort was relatively well functioning at baseline. The relatively large number of participants who did not return for follow-up might have biased the results. However, similar results obtained for handgrip strength and arm lean mass suggest that our results are not limited to lower extremity strength. Examination of changes across additional time points or over a longer period of follow-up might have helped to reduce any measurement error that could have confounded the associations between muscle mass and strength measured across only two time points. Moreover, we did not determine whether other potential confounders, such as dietary intake or neurological function, influenced the observed changes. Another potential limitation was the lack of follow-up CT scan data, which will be available after 5 years of follow-up. These data will allow us to examine changes in muscle fat infiltration as a function of strength loss.

Summary

The loss of strength in these older men and women was much more rapid than the concomitant loss of muscle mass, suggesting a significant decline in the quality of muscle. Additionally, individuals who maintained or even gained lean mass were not able to significantly prevent their loss of strength. Although it may be important to preserve lean mass to prevent strength decline in old age, a considerable amount of the age-dependent strength decline is not explained by the loss of muscle mass alone. Therefore, we can put forth an alternative hypothesis that, in addition to muscle quantity, muscle quality may be an important determinant of loss of strength with aging. Further studies are required to identify other risk factors for the decline in strength with aging so that more targeted interventions can be planned to prevent or slow the decline, thus maintaining overall function of older men and women.

ACKNOWLEDGMENTS

This research was supported in part by the Intramural Research Program of the National Institutes of Health, National Institute on Aging (N01-AG-6-2101, N01-AG-6-2103, N01-AG-6-2106, and K01-AG-00851; to BHG).

Drs. Goodpaster and Park contributed equally to this manuscript and should be considered as co-first authors.

Dr. Park is now with the Department of Internal Medicine, Pochon Cha University, Pochon, Korea.

Address correspondence to Bret H. Goodpaster, PhD, Department of Medicine, MUH-N809, University of Pittsburgh Medical Center, Pittsburgh, PA 15213. E-mail: bgood@pitt.edu

REFERENCES

1. Metter EJ, Talbot LA, Schrager M, Conwit R. Skeletal muscle strength as a predictor of all-cause mortality in healthy men. *J Gerontol Biol Sci*. 2002;57A:B359–B365.
2. Laukkanen P, Heikkinen E, Kauppinen M. Muscle strength and mobility as predictors of survival in 75-84-year-old people. *Age Ageing*. 1995;24:468–473.
3. Rantanen T, Harris T, Leveille SG, et al. Muscle strength and body mass index as long-term predictors of mortality in initially healthy men. *J Gerontol Med Sci*. 2000;55A:M168–M173.
4. Rantanen T, Volpato S, Ferrucci L, Heikkinen E, Fried LP, Guralnik JM. Handgrip strength and cause-specific and total mortality in older disabled women: exploring the mechanism. *J Am Geriatr Soc*. 2003;51:636–641.
5. Newman A, Kupelian V, Visser M, et al. Strength, but not muscle mass, is associated with mortality in the Health, Aging and Body Composition Study cohort. *J Gerontol Biol Sci Med Sci*. 2006;61A:72–77.
6. Harris T. Muscle mass and strength: relation to function in population studies. *J Nutr*. 1997;127:1004S–1006S.
7. Metter EJ, Conwit R, Tobin J, Fozard JL. Age-associated loss of power and strength in the upper extremities in women and men. *J Gerontol Biol Sci*. 1997;52A:B267–B276.
8. Metter EJ, Lynch N, Conwit R, Lindle R, Tobin J, Hurley B. Muscle quality and age: cross-sectional and longitudinal comparisons. *J Gerontol Biol Sci*. 1999;54A:B207–B218.
9. Doherty TJ. Invited review: Aging and sarcopenia. *J Appl Physiol*. 2003;95:1717–1727.
10. Roubenoff R, Hughes VA. Sarcopenia: current concepts. *J Gerontol Med Sci*. 2000;55A:M716–M724.
11. Newman AB, Haggerty CL, Goodpaster B, et al. Strength and muscle quality in a well-functioning cohort of older adults: the Health, Aging and Body Composition study. *J Am Geriatr Soc*. 2003;51:323–330.
12. Visser M, Kritchevsky SB, Goodpaster BH, et al. Leg muscle mass and composition in relation to lower extremity performance in men and women aged 70 to 79: the Health, Aging and Body Composition study. *J Am Geriatr Soc*. 2002;50:897–904.
13. Evans WJ, Campbell WW. Sarcopenia and age-related changes in body composition and functional capacity. *J Nutr*. 1993;123:465–468.
14. Rantanen T, Guralnik JM, Foley D, et al. Midlife hand grip strength as a predictor of old age disability. *JAMA*. 1999;281:558–560.
15. Rantanen T. Muscle strength, disability and mortality. *Scand J Med Sci Sports*. 2003;13:3–8.
16. Lord SR, Ward JA, Williams P, Anstey KJ. Physiological factors associated with falls in older community-dwelling women. *J Am Geriatr Soc*. 1994;42:1110–1117.
17. Rantanen T, Avlund K, Suominen H, Schroll M, Frandin K, Pertti E. Muscle strength as a predictor of onset of ADL dependence in people aged 75 years. *Aging Clin Exp Res*. 2002;14:10–15.
18. Visser M, Pahor M, Tylavsky F, et al. One- and two-year change in body composition as measured by DXA in a population-based cohort of older men and women. *J Appl Physiol*. 2003;94:2368–2374.
19. Visser M, Fuerst T, Lang T, Salamone L, Harris TB. Validity of fan-beam dual-energy X-ray absorptiometry for measuring fat-free mass and leg muscle mass. Health, Aging, and Body Composition Study–Dual-Energy X-ray Absorptiometry and Body Composition Working Group. *J Appl Physiol*. 1999;87:1513–1520.
20. Goodpaster BH, Carlson CL, Visser M, et al. Attenuation of skeletal muscle and strength in the elderly: the Health ABC Study. *J Appl Physiol*. 2001;90:2157–2165.
21. Mazess RB, Barden HS, Bisek JP, Hanson J. Dual-energy x-ray absorptiometry for total-body and regional bone-mineral and soft-tissue composition. *Am J Clin Nutr*. 1990;51:1106–1112.
22. Heymsfield SB, Gallagher D, Visser M, Nuñez C, Wang ZM. Measurement of skeletal muscle: laboratory and epidemiological methods. *J Gerontol A Biol Sci Med Sci*. 1995 Nov;50 Spec No:23–29.
23. Goodpaster BH, Kelley DE, Thaete FL, He J, Ross R. Skeletal muscle attenuation determined by computed tomography is associated with skeletal muscle lipid content. *J Appl Physiol*. 2000;89:104–110.
24. Simonsick EM, Newman AB, Nevitt MC, et al. Measuring higher level physical function in well-functioning older adults: expanding familiar approaches in the Health ABC study. *J Gerontol Med Sci*. 2001;56:M644–M649.
25. Larsson L, Grimby G, Karlsson J. Muscle strength and speed of movement in relation to age and muscle morphology. *J Appl Physiol*. 1979;46:451–456.
26. Lindle RS, Metter EJ, Lynch NA, et al. Age and gender comparisons of muscle strength in 654 women and men aged 20–93 yr. *J Appl Physiol*. 1997;83:1581–1587.
27. Frontera WR, Hughes VA, Fielding RA, Fiatarone MA, Evans WJ, Roubenoff R. Aging of skeletal muscle: a 12-yr longitudinal study. *J Appl Physiol*. 2000;88:1321–1326.
28. Schiller BC, Casas YG, Tracy BL, DeSouza CA, Seals DR. Age-related declines in knee extensor strength and physical performance in healthy Hispanic and Caucasian women. *J Gerontol Biol Sci*. 2000;55A:B563–B569.
29. Hughes VA, Frontera WR, Roubenoff R, Evans WJ, Singh MA. Longitudinal changes in body composition in older men and women: role of body weight change and physical activity. *Am J Clin Nutr*. 2002;76:473–481.
30. Lynch NA, Metter EJ, Lindle RS, et al. Muscle quality. I. Age-associated differences between arm and leg muscle groups. *J Appl Physiol*. 1999;86:188–194.
31. Rantanen T, Masaki K, Foley D, Izmirlian G, White L, Guralnik JM. Grip strength changes over 27 yr in Japanese-American men. *J Appl Physiol*. 1998;85:2047–2053.
32. Brooks SV, Faulkner JA. Skeletal muscle weakness in old age: underlying mechanisms. *Med Sci Sports Exer*. 1994;26:432–439.
33. Young A, Stokes M, Crowe M. Size and strength of the quadriceps muscle of old and young women. *Eur J Clin Invest*. 1984;14:282–287.
34. Trappe S, Gallagher P, Harber M, Carrithers J, Fluckey J, Trappe T. Single muscle fibre contractile properties in young and old men and women. *J Physiol*. 2003;552:47–58.
35. Overend TJ, Cunningham DA, Kramer JF, Lefcoe MS, Paterson DH. Knee extensor and knee flexor strength: cross-sectional area ratios in young and elderly men. *J Gerontol Med Sci*. 1992;47A:M204–M210.
36. Reed RL, Pearlmutter L, Yochum K, Meredith KE, Mooradian AD. The relationship between muscle mass and muscle strength in the elderly. *J Am Geriatr Soc*. 1991;39:555–561.
37. Lexell J, Downham D, Sjostrom M. Distribution of different fibre types in human skeletal muscles. Fibre type arrangement in m. vastus lateralis from three groups of healthy men between 15 and 83 years. *J Neurol Sci*. 1986;72:211–222.
38. Roubenoff R. Catabolism of aging: is it an inflammatory process? *Curr Opin Clin Nutr Metab Care*. 2003;6:295–299.
39. Frontera WR, Meredith CN, O'Reilly KP, Knuttgen HG, Evans WJ. Strength conditioning in older men: skeletal muscle hypertrophy and improved function. *J Appl Physiol*. 1988;64:1038–1044.
40. Trappe S, Godard M, Gallagher P, Carroll C, Rowden G, Porter D. Resistance training improves single muscle fiber contractile function in older women. *Am J Physiol Cell Physiol*. 2001;281:C398–C406.

Received January 18, 2006
Accepted April 24, 2006
Decision Editor: Luigi Ferrucci, MD, PhD