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Age-Associated Loss of Power and Strength in the Upper Extremities in Women and Men

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Cross-sectional and longitudinal age-associated reductions in power and isometric strength are described for the upper extremities. Over a 25-year period, repeated measures were taken approximately every 2 years from men and women in the Baltimore Longitudinal Study of Aging (BLSA). The longitudinal measures covered an average 9.6 years, range 1–25 years for men and an average 4.6 years, range 1–8 years for women. Strength and power declined beginning by age 40 in both women and men. Thereafter, power declined about 10% more than strength in men, while no significant differences were found in women. Age had a statistically independent influence on strength and power measures after adjusting for gender, height, weight, caloric expenditure, and muscle mass. Twenty-five-year longitudinal analyses in men confirmed the declines observed cross-sectionally, while no changes were observed in women over the 4–5 years of longitudinal data available. Further longitudinal studies are needed to understand the relationships between strength and power losses with age in women. The differences between power and strength changes with age in men argue for the importance of factors other than strength affecting power.

AGING is associated with declines in upper and lower extremity muscle strength (Asmussen & Heeboll-Nielsen, 1962; Clement, 1974; Larsson et al., 1979; Murray et al., 1980, 1985; Mathiowetz et al., 1985; Viitasalo et al., 1985; Vandervoort and McComas, 1986; Weldon et al., 1988; Borges, 1989; Fisher et al., 1990; Kallman et al., 1990; Frontera et al., 1991; Phillips et al., 1992) and power (Margaria et al., 1966; Shock and Norris, 1970; Bosco and Komi, 1980; Bassey and Short, 1990; Bassey et al., 1992) based primarily on cross-sectional studies. Few longitudinal studies have been done that included large numbers of subjects and that have considered the entire adult age span (Clement, 1974; Kallman et al., 1990). Furthermore, we are unaware of any studies that directly compare age differences in power and strength in men and women across the adult life span.

Strength is force generated during or while attempting a given movement. Age-associated losses in strength are primarily attributed to changes in muscle, particularly to decreases in the number and size of muscle fibers (Lexell et al., 1983, 1986) resulting in muscle loss. Fiber losses are associated with changes in the distribution of muscle fiber types (Larsson et al., 1979), losses and reorganization of motor units (Campbell et al., 1973; Doherty and Brown, 1993), contraction injuries (Faulkner et al., 1995), and other factors. The importance of age changes in neuromuscular as opposed to central nervous system mechanisms has been shown by studies of Phillips et al. (1992) and Brown and Hasser (1996), who found that neural stimulation during maximal muscle strength did not improve performance.

Power is of particular interest in studies of aging because it may be more directly related to losses of physical function than isometric strength (Bassey and Short, 1990; Bassey et al., 1992). Furthermore, power declines to a greater extent than strength in old age (Margaria et al., 1966; Shock and Norris, 1970; Bosco and Komi, 1980; Bassey and Short, 1990; Bassey et al., 1992), but only one study (Shock and Norris, 1970) directly compared power and strength in men.

Power is a measure of the work (force × distance) performed per unit time. Power depends on the ability to generate force as well as extremity velocity, and to coordinate movement (Sergeant et al., 1981; Froese and Houston, 1987). Brooks and Faulkner (1994) argue that the power loss is related to muscle atrophy and to changes in force generation by the remaining muscle fibers, but this cannot explain the differences in strength and power losses with age. The likely explanation includes the changes in muscle that reduce strength (as suggested by Brooks and Faulkner, 1994), plus changes in nervous system control of the motor system that slow the time and speed of response. The loss of power with increasing age is likely related to slower movement and reaction times (Fozard et al., 1994) resulting from reorganization of spinal and central nervous system control and changes in the neuromuscular system. With increasing age, muscle changes occur in the neuromuscular apparatus that will affect movement velocity and coordination, including increases in muscle contraction and relaxation times (Vandervoort and McComas, 1986), and slowing of nerve conduction (Wagman and Lesse, 1952; Norris et al., 1953; Lafratta and Canestrari, 1966) which lead to a longer time to reach peak force with an accompanying decline in power generation. Therefore, combining analysis of strength and power may provide a better tool for understanding age-associated declines in functional performance.

Power is measured by a variety of methods, two of which are of particular interest for this study. First, short-term power is maximal work performed over a short period of time. The goal is to reach maximum work early and to maintain that level of exertion for the duration of the measurement. This is the method used in the present study. Second, immediate or explosive power is work done within the first second of activity. Both forms of power are important for speed and accuracy of short movements and, therefore, for many routine functions that characterize activities of daily living (ADLs) and functional capability. Immediate power has been studied most extensively in the lower extremities by jumping (Bosco and Komi, 1980; Froese and Houston, 1987) or by single leg extension (Bassey and Short, 1990; Bassey et al., 1992). Cross-sectional studies suggest that immediate power may begin to decline at an earlier age than maximum strength and peaks between 20 and 30 years of age.

The present study compares relative and absolute differences in arm strength and power of women and men across the adult life span using arm cranking over a period of 10–15 seconds to measure power and isometric strength in similar muscle groups. In addition, within any grouping by gender and age, differences occur in muscle mass, weight, height, and activity level, all of which will influence strength and power, though not necessarily to the same degree. Therefore, the second purpose of this study is to examine whether age has a statistically independent contribution to strength and power when considering these other factors.

To our knowledge, the 25 years of follow-up represent the longest collection of strength and power data available in longitudinal studies. The study extends the initial cross-sectional results from Shock and Norris (1970) based on 218 male participants in the Baltimore Longitudinal Study of Aging (BLSA).

Methods

Subjects consisted of 993 male and 184 female participants in the BLSA. A full description of the BLSA and its research participants was published in Shock et al. (1984). The strength and power measurements began in 1960 and were collected until 1985 for the men, and from 1978 to 1985 for the women. The subjects were examined every one to two years. They were well educated and considered themselves well-off and healthy. No specific health selection criteria were used to screen participants whose data are included in this analysis.

Health status was estimated from a medical evaluation at each visit to determine whether health factors had an important contribution to strength and power in the study. The evaluation included medical questionnaires, physical and cardiovascular examinations consisting of an angina questionnaire, a resting electrocardiogram, and exercise electrocardiogram. Based on the cardiovascular evaluation, subjects were rated as having no known, possible, or definite coronary heart disease. Based on the health questionnaire, medication usage and physical examination, subjects were rated on a 5-point severity scale for musculoskeletal problems. Mortality was through an ongoing BLSA program to identify participant deaths that allow for tracking of more than 98% of current and former participants.

Total body muscle mass was estimated by 24-hour creatinine excretion using standard clinical procedures (Tzankoff and Norris, 1977). Twenty-four-hour creatinine excretion has been a widely used method to estimate muscle mass (Forbes and Bruining, 1976; Heymsfield et al., 1983). Muscle is estimated to be 17 to 20 kg whole wet mass/g urinary creatinine.

Activity levels were estimated through a questionnaire that asked how much time was spent on a list of 108 activities (McGandy et al., 1966; Shock et al., 1984; Verbrugge et al., 1996). The time was converted to caloric expenditure as previously described by McGandy et al. (1966).

Power was measured as described by Shock and Norris (1970). A bicycle was converted to act as a drive shaft to power a calibrated automobile generator. The pedal arms were replaced with hand-grips while the chain drove a 12-inch flywheel replacing the rear bicycle wheel. A drive sprocket wheel was attached to the flywheel and by chain to a sprocket wheel mounted on the generator. The generator was connected to a meter. The system was calibrated by determining the power required to drive the system between 20 and 200 rpm and considered windage, friction, electrical losses, power output of the generator, and meter loss. Power was expressed in kilograms/minute.

Subjects were recumbent on a reinforced bed that limited power losses caused by bed movement. The bicycle was rigidly suspended above the bed. The hand cranks were positioned to achieve a comfortable cranking position with the arms above the body plane. The apparatus allowed for full range of motion at the elbows. Subjects were instructed to perform a maximum effort for 10–15 seconds at each of 4 load settings (1–4 amps). The order in which the loads were presented was systematically varied (Shock and Norris, 1970). The maximum scale reading was converted to power units by a calibration curve. Between each trial, subjects rested for at least 30 seconds.

Individual performance varied, based on the load. At the lowest amperage, subjects cranked the fastest with the least resistance, and at the highest the cranking was slower but against greater resistance. Total power was calculated as the sum of the power generated against the four workloads and will be called *power*.

Isometric muscle strength was tested in an apparatus designed to measure four tangential components. Subjects were seated with the upper arms perpendicular to the floor with the forearm parallel to the anterior-posterior axis and perpendicular to the head-to-seat axis. Shoulders were supported by a backboard and by shoulder straps. Hands lay on 1-inch-thick wooden grips connected by wires to a supporting frame. Subjects pulled against the grips in four ways: up, down, forward, and backward along the axis of the forearm. Each direction was tested three times with the maximal value accepted. A 10-second rest period occurred between trials. Grip strength was measured with a hand dynanometer as described by Kallman et al. (1990). Total strength scores were calculated by summing the eight arm measurements and both grip strengths, and will be referred to as *strength*. Test-retest reliabilities for power and total strength were estimated by taking measurements on consecutive days. The correlation for total muscle strength was .87 ($n = 29, p < .001$), and .83 ($n = 30, p < .001$) for power.

Data analysis. — Statistical analyses were completed using SPSS for Windows. The same equipment was used throughout the study, with replacement and repairs of components as needed. The equipment was calibrated on a regular basis. There was no evidence for any large sudden changes in the measurements over time. A single technician made all measurements during a time period, although several technicians spanned the 25 years of data collection. Preliminary analyses identified a small systematic linear downward drift in the power (.004 kg/year for men, $p < .01$, $r^2 = .017$; .007 kg/yr for women, $p < .03$, $r^2 = .021$) and strength by year that was unrelated to gender or age. Adjustments were made to the data by regressing power and strength on date to obtain predicted values. The predicted values were subtracted from the average predicted value for 1958–1962 for men and 1978–1982 for women and were added to the actual measurement for the visit. The corrected data no longer had a significant correlation with the date.

Preliminary analyses were conducted to determine whether health factors were important in this study by regressing power and strength on time to death, coronary heart disease, and musculoskeletal problems while controlling for sex, age, and age-squared. No significant relationships were found between strength or power and time to death or coronary heart disease. Power ($p < .05$, $r = .04$) but not strength ($p = .09$, $r = .03$) significantly correlated with musculoskeletal problems. The relationships between these health-related factors and strength and power were minimal and, in our judgment, would not adversely affect the interpretation of the results. Accordingly, all subjects were included in the cross-sectional and longitudinal analyses.

Cross-sectional analyses used data for the last visit in which these tests were performed. Preliminary analysis suggested that the relationship of strength and power was curvilinear with age. So, in addition to linear regression, two more regression strategies were used to examine the relationships. First, a quadratic age term was included. Second, piecewise regression was modeled using the NLIN option in SPSS to apply a conditional term to the regression equation that would alter the slope of the line above an age. The goal was to determine if and at what age a change occurred in the linear slope. For some models, separate analyses were done for women and men; for others, gender was considered as a dummy variable. To compare relative age changes, power and strength were compared by adjusting the values per decade as the percentage of the mean value for 20-year-olds for each gender.

Path analysis (Loehlin, 1987) was used to examine the relationships between age and gender on strength and power when considering height, weight, caloric expenditure, and muscle mass. Computations were made using AMOS 3.6 (SmallWaters Corp., Chicago, 1996). AMOS allows for the simultaneous analysis of a system of linear equations. We used this method to test the specific model as described below to examine the relationships between the measured variables, but not for exploratory analysis to optimize their relationships. We were specifically interested in the relationships between the variables as modeled and not in the identification of some latent structure between the variables.

Longitudinal data were examined using a two-stage model. Linear regression was used to estimate age changes in power or strength for each subject. Then the individual changes were used to estimate power and strength at the age of first and last evaluation for each subject. Subjects were then grouped based on their age of first evaluation. Men were grouped by age decade at initial evaluation, while women were grouped based on 20-year intervals. Age differences in slopes and differences in slopes between strength and power were calculated by age group using weighted least squares with weighting based on the number of subject measurements. To compare power and strength, both measures were converted to a percentage of the 20-year-old age group's performance.

Results

Cross-sectional Analysis

The distribution of subjects by age decade is presented in Table 1. With increasing age, height and muscle mass (creatinine excretion) declined, while weight and caloric expenditure did not change until later decades of life. Younger men and women were taller, had more muscle mass, and were leaner than older subjects.

Power was measured against four different loads that affected maximal power output. Figure 1 shows cross-sectional regression analyses of power for each work load (1 to 4 amperes) by age and age-squared for women and men. Preliminary analysis of the data showed a curvilinear pattern to the data with age-squared significantly improving the explained variance. Power increased as the load increased from one to four amperes. The largest increase occurred between one and two amperes. Older age was associated with a decline in power at all four loads. The power level was lower at all amperes for women than for men. Power declined beginning in the 20s in women, and 30s in men. The shapes of the curves are the same for each of the four amperages and between men and women when the data are expressed as percentage change from 20-year-olds. Because the pattern of change with age was the same for each load, the sum of power generated at the four levels was accepted as the best estimate of overall power performance.

Mean total strength and power were calculated by age decade (Figure 2). For men, significant age differences were found in strength ($p < .001$) and power ($p < .001$), with both peaking in the 30s and then showing a steady decline. In women, power and strength declined with age ($p < .001$), with the changes beginning in the 50s when examined by age decade.

Three regression models were employed to characterize the age-associated changes in strength and power by gender: linear, quadratic, and piecewise (a linear model with a point change in slope). Linear regression may not provide as good an overall description of the data when there are differences in rate of change of strength and power as shown in Figure 2. A quadratic regression provides a smooth curve that describes function well but does not identify an age or age range where a change occurs in the rate of loss. The piecewise model was used to identify where a change in slope occurred. A linear model best fit the age changes in power for women ($r^2 = .27$). The quadratic model significantly improved the fit over the linear model

Table 1: Characterization by Age Group and Gender for Cross-sectional Analysis

	Cross-sectional (Age Groups)						
	20	30	40	50	60	70	80
Women							
Subjects	25	60	36	46	48	39	12
Age (yrs)	26.8	34.6	44.5	55.9	65.1	74.7	82.4
	(2.9)	(3.2)	(3.2)	(2.9)	(3.0)	(2.7)	(1.9)
Creatinine excretion (mg/24 hrs)	1095	1024	1032	983	873	805	697
	(251)	(245)	(232)	(249)	(196)	(181)	(158)
Height (cm)	167.6	164.8	164.7	162.8	161.6	159.6	156.6
	(6.2)	(6.2)	(5.6)	(7.0)	(7.2)	(7.2)	(6.0)
Weight (kg)	61.8	61.9	63.0	64.4	61.4	62.3	52.3
	(7.5)	(9.3)	(7.9)	(11.8)	(10.0)	(12.0)	(5.7)
Daily caloric expenditure (cal/d)	2730	2788	2850	2777	2657	2590	2206
	(356)	(499)	(407)	(558)	(437)	(465)	(211)
Men							
Subjects	67	142	144	210	226	214	69
Age (yrs)	26.8	35.0	44.3	55.5	64.7	74.8	83.9
	(2.5)	(2.9)	(3.0)	(3.0)	(2.9)	(2.5)	(3.8)
Creatinine excretion (mg/24 hrs)	1775	1770	1694	1601	1450	1285	1165
	(320)	(308)	(308)	(226)	(217)	(261)	(234)
Height (cm)	179.3	179.7	178.3	176.5	176.1	173.4	172.8
	(6.7)	(6.6)	(6.5)	(6.8)	(6.3)	(5.7)	(5.7)
Weight (kg)	78.1	81.8	85.2	80.9	79.0	74.8	73.0
	(13.0)	(11.1)	(14.4)	(11.4)	(10.8)	(9.8)	(9.8)
Daily caloric expenditure (cal/d)	3547	3740	3744	3461	3342	3121	3048
	(759)	(769)	(833)	(576)	(556)	(464)	(490)

Note: Numbers in parentheses are standard deviations.

for strength in women (r^2 = .32), and for men (r^2 = .43 for strength and r^2 = .38 for power). Piecewise regression accounted for similar or slightly greater variance than the quadratic model for strength (r^2 = .33) in women, and for strength (r^2 = .44) and power (r^2 = .38) in men. The piecewise model (Figure 3) shows a change in slope at approximately 40 years of age for strength (39.8 years, 95% confidence interval [CI] = 36.2–43.3 years) and power (40.1 years, CI = 36.1–43.5 years) in men, and age 44 years (CI = 33.1–55.2 years) for strength in women. For each piecewise model, the CI for the initial slope included zero, implying that by these models no important change in strength may occur up to about age 40. Comparing Figures 2 and 3, the piecewise model fits the actual data more closely in the 70- and 80-year-old groups than the quadratic.

To compare relative age changes between strength and power, each was expressed as a percent of the average power for 20-year-olds by gender (Figure 2). Strength and power declined 34 and 42% in men, and 32 and 46% in women from the 20-year-olds to the 80-year-olds. One-way analysis of variance (ANOVA) found the percentage difference of strength and power by age decade differed for men ($p < .001$), but not for women ($p = .33$). Post hoc analysis using Tukey's procedure indicated that 70- and 80-year-old men showed greater differences between strength and power than other younger age groups. Eighty-year-old men had 10% greater difference between strength and power than 20-year-olds.

Because the age groups (Table 1) differed in height, weight, muscle mass (24-hour creatinine excretion), and self-reported activity levels (caloric expenditure), the relationships between these variables on strength and power were examined using path analysis (Figure 4), allowing us to estimate the indirect effect of age on strength and power through these variables and the direct effects after accounting for them. The question asked was whether the relationship between age and strength, and age and power persisted when the other variables were considered as modeled. The model (Figure 4) has a series of arrows representing the proposed relationships between two variables. Gender was a grouping variable, while age has direct effects on the other variables (height, weight, activity [caloric expenditure], muscle mass [creatinine excretion], strength, and power). In addition, age has indirect effects on strength and power. For example, age affects height which affects power. Further, the model considers height as affecting weight, activity, muscle mass, strength, and power. Weight affects caloric expenditure, muscle mass, strength, and power. Activity (caloric expenditure) affects muscle mass, strength, and power. Muscle mass (creatinine excretion) affects strength and power. The numbers in the models for women and men are standardized coefficients that reflect the amount that a normalized variable at the end of the arrow changes as a function of a one standard deviation change in the normalized variable at the beginning of the arrow.

The model shows a reasonable fit to the data with chi-square = 9.683, df = 10, p = .47, and by permutation test (Arbuckle, 1996), 0/5039 permutations improved the model fit. For men, the multiple squared correlation (an estimate of the proportion of a variables variance accounted for by

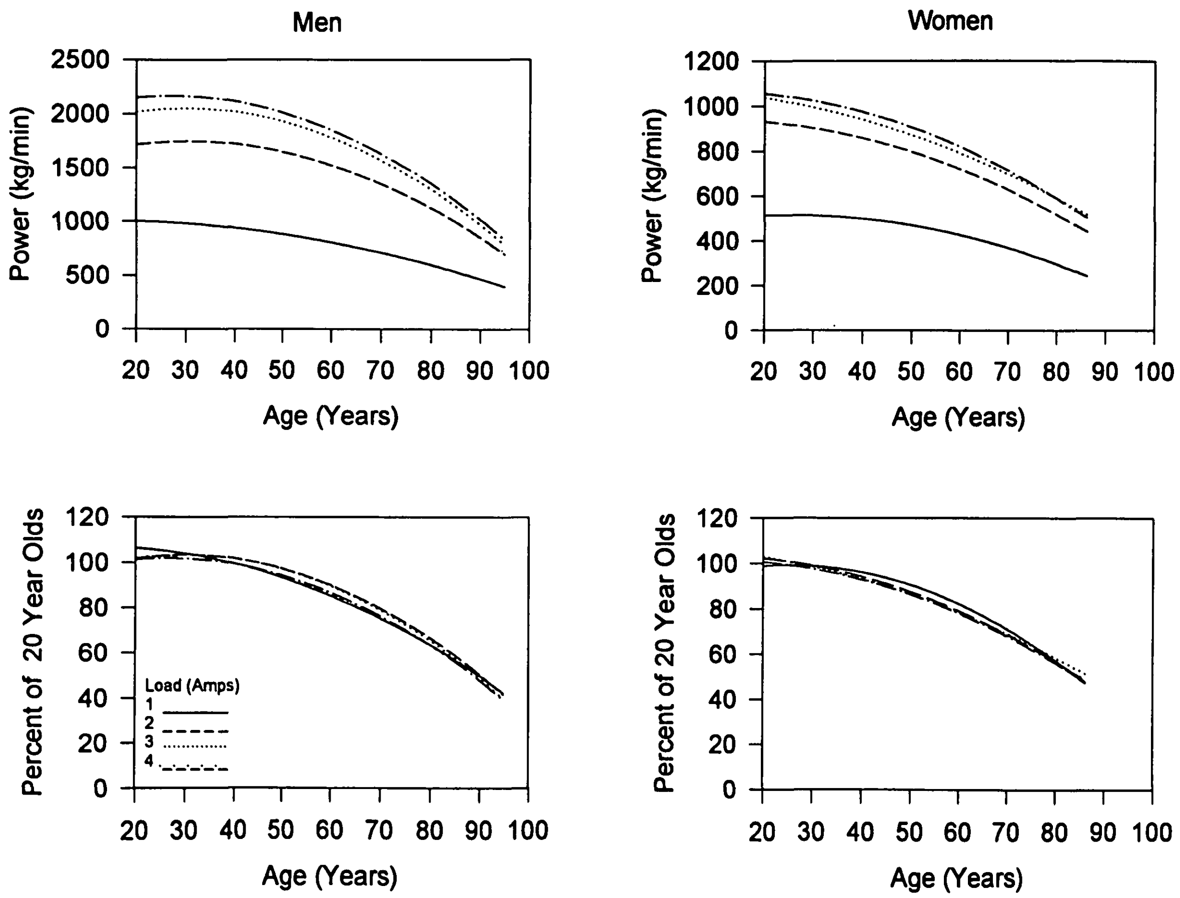

Figure 1. Regression equations of power production against four different amperage loads on the generator motor. All equations include a quadratic term for age.

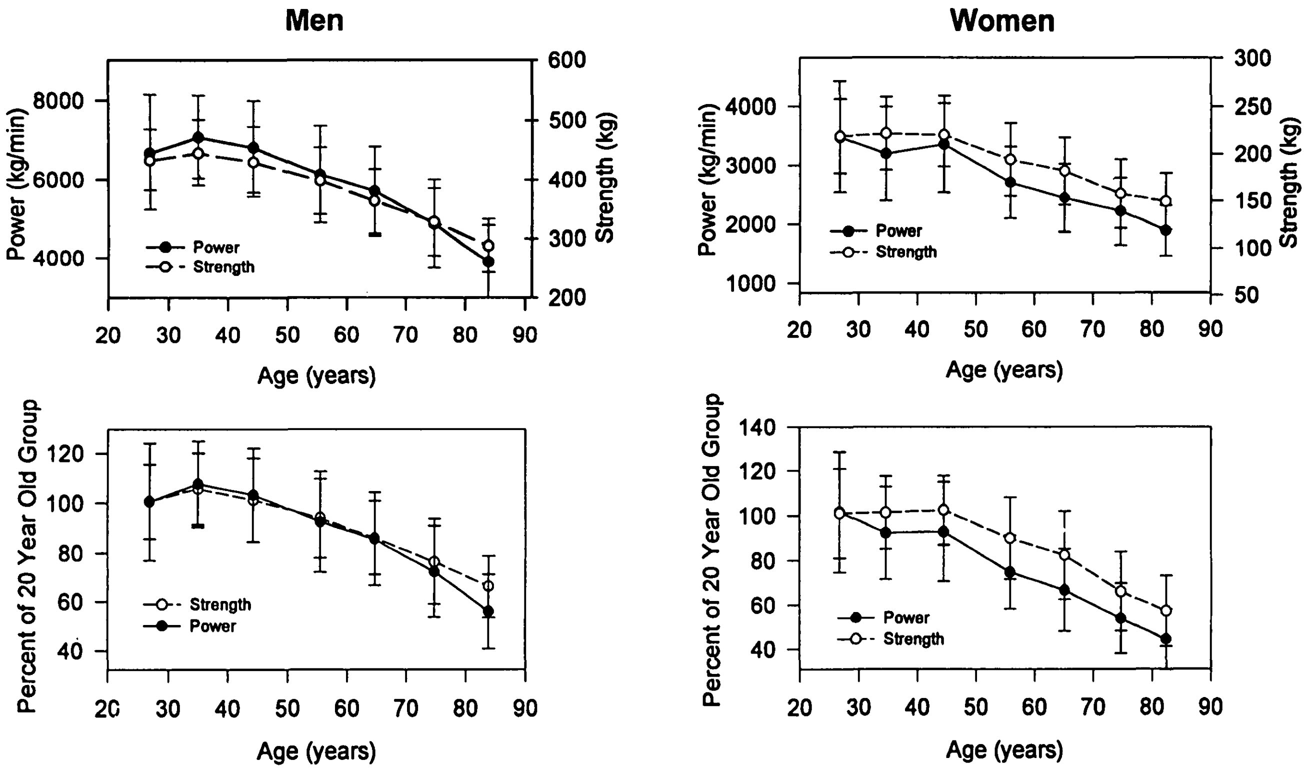

Figure 2. Average power and strength generated by subjects within each age decade (with standard deviations) for men and women. The lower graphs show strength and power expressed as a percentage of the values obtained by the 20-year-old groups for men and women (with standard deviations).

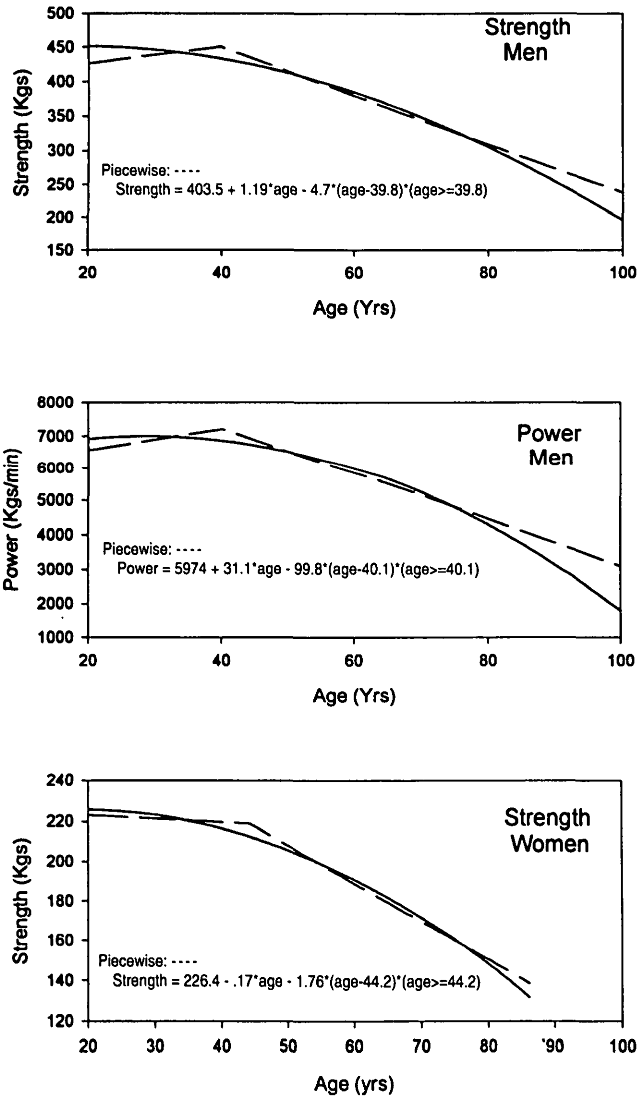

Figure 3. A comparison of piecewise and quadratic regression for strength and power in men and strength in women. Analysis of the power data in women found that a linear model was adequate to explain the data and is not shown.

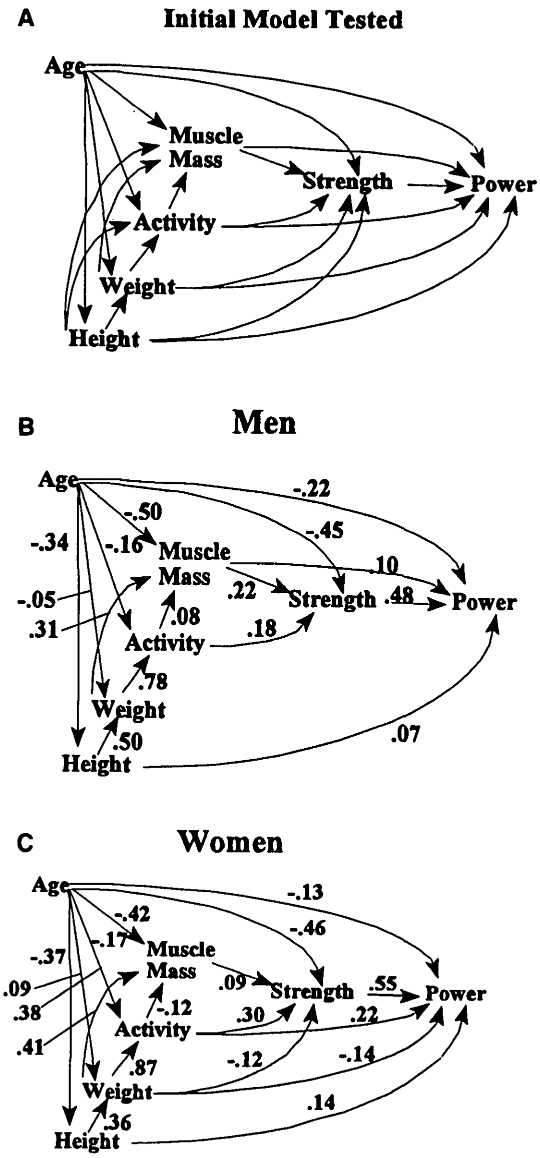

Figure 4. Path analysis examing the relationships between strength and power on age, gender, height, weight, caloric expenditure, and muscle mass. (A) Initial model that was based on assumed relationships between the variables; (B) Final model for men; (C) Final model for women. The model assumed that age and gender were exogenous variables that influenced height, weight, caloric expenditure, and muscle mass, and had independent effects on strength and power. Each variable has a series of arrows that reflect the direction of the relationship between the variables. Error terms (not shown) were included for each endogenous variable. Standardized coefficients are shown for each path that reflect the amount that a normalized variable will change for a unit change from the variable at the other end of the arrow.

predictors, Arbuckle, 1996, p. 347) for strength was .49 and power was .54, while for women strength was .36 and power was .56. Age had independent effects on strength and power after considering size and activity. The effect was greater on strength, with coefficients of –.45 (men) and –.46 (women), than for power, with coefficients of –.22 (men) and –.13 (women). Strength had the greatest direct effect on power (coefficients of .48 for men and .55 for women), which was indirectly affected by age.

Longitudinal Analysis

Longitudinal measures for strength were taken from 837 men followed for an average of 9.57 years (range 1–25 years), and for power from 768 men followed for an average of 9.54 years (Table 2A). For women, longitudinal data were available from 106 women for strength followed for 3.9 years, and from 44 women for power followed for 4.6 years (Table 2B). For the men, both power ($p < .001$) and strength ($p < .001$) declined longitudinally. The pattern of decline was similar to that observed in the cross-sectional analysis (Figure 5A). In particular, the rate of decline of power with aging was greater than that for strength ($p < .05$). For women, no longitudinal declines were found for either strength or power, although the cross-sectional decline was found between age groups (Figure 5B).

Table 2A. Longitudinal Measures of Strength and Power in Men

	Longitudinal (Age Groups)						
	20	30	40	50	60	70	80
Power							
Subjects	95	159	181	158	90	76	9
Initial age	26.5	34.7	45.1	54.1	64.1	73.3	82.9
	(2.9)	(3.0)	(2.9)	(3.0)	(2.9)	(2.5)	(2.7)
Final age	34.9	45.0	57.5	63.9	72.4	77.9	85.1
	(2.9)	(7.1)	(6.6)	(6.3)	(5.3)	(4.0)	(3.4)
Initial power (kg/min)	7142	7005	6504	6365	5865	4854	4003
	(1200)	(1061)	(1186)	(1027)	(999)	(1134)	(699)
Final power (kg/min)	7238	6894	6201	5818	5016	4506	3697
	(1216)	(1162)	(1121)	(1143)	(1137)	(1039)	(457)
Strength							
Subjects	96	172	179	168	99	103	20
Initial age	26.7	34.8	45.1	54.3	64.3	73.6	85.1
	(2.7)	(3.0)	(2.8)	(3.0)	(2.8)	(2.6)	(4.9)
Final age	36.1	46.2	58.6	65.5	72.8	78.3	87.0
	(5.5)	(7.4)	(7.1)	(6.4)	(5.8)	(4.3)	(5.0)
Initial strength (kg/min)	426.5	435.2	417.4	407.2	377.8	337.4	289.4
	(52.6)	(53.7)	(54.2)	(68.8)	(57.9)	(55.1)	(41.6)
Final strength (kg/min)	441.6	430.0	392.1	362.1	339.4	309.0	287.0
	(55.5)	(53.2)	(50.1)	(59.5)	(55.9)	(51.4)	(47.1)

Note: Numbers in parentheses are standard deviations.

Table 2B: Longitudinal Measures of Strength and Power in Women

	Longitudinal (Age Groups)		
	30	50	70
Power			
Subjects	21	18	5
Initial age	29.7	50.3	64.4
	(5.1)	(6.1)	(5.0)
Final age	34.0	55.3	68.8
	(6.0)	(6.8)	(4.9)
Initial power (kg/min)	3574	2774	2240
	(768)	(819)	(1134)
Final power (kg/min)	3646	3078	2148
	(885)	(758)	(599)
Strength			
Subjects	38	34	34
Initial age	32.3	50.9	68.2
	(5.1)	(5.4)	(6.5)
Final age	36.6	55.0	71.4
	(5.5)	(5.8)	(6.4)
Initial strength (kg/min)	211.9	199.6	170.1
	(36.0)	(29.6)	(33.0)
Final strength (kg/min)	221.9	206.1	170.3
	(42.9)	(37.2)	(27.9)

Note: Numbers in parentheses are standard deviations.

Discussion

Age-associated declines were observed in short-term power generation in an arm cranking task and isometric arm strength as previously described for men by Shock and Norris (1970), and in women. Preservation of both power and strength was observed to about age 40, after which declines became apparent. The age decline after age 40 is somewhat earlier than is often suggested from the literature. For women, loss of power began at even a younger age based on the regression analysis, while obvious differences were apparent by the 50s when examined by age decades (Figure 2). The age decline in power was about 10% greater than the decline in strength from age 20 to 80 years (significant for men but not women).

Both longitudinal and cross-sectional data for women exhibited a less clear age-associated loss of strength and power than for men. No longitudinal changes in strength or power were found over a 4-year follow-up period. In the cross-sectional data, the variance accounted for by age was less in women than men for both strength and power. Clearly, further longitudinal studies are needed, with more women studied for a longer period of time.

In the cross-sectional analysis in men (Figure 2), the most profound differences between strength and power were found in the older decades, although the regression analysis (Figure 3) clearly show that changes occur at a younger age. The 25 years of longitudinal data (Figure 5A) bring out the age difference in power and strength, and suggest that the difference may be greater than suggested by cross-sectional analysis. One factor contributing to the difference between cross-sectional and longitudinal analyses in men is selection bias. In cross-sectional studies, older individuals tend to be healthier at entry than men longitudinally followed to that age (Metter et al., 1992). Thus, some aspects of health change in men with increasing age may adversely affect power to a greater extent than strength.

The strength and power measurements were based on equipment developed in 1960 and used for the entire period of the study. To give current relevance to the isometric measurement, we compared strength from this study (last collected in 1985) in 265 subjects who after approximately

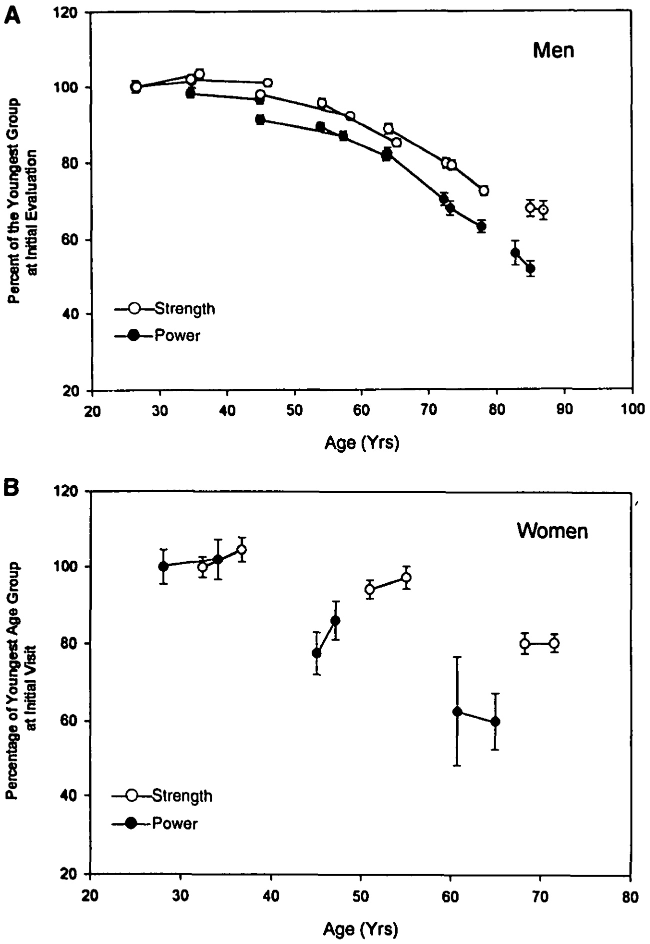

Figure 5. Longitudinal analysis of strength and power changes in men (A) and women (B), who were grouped based on the age decade in men and 20-year interval in women when the initial measure was made. Power and strength were expressed as the percentage of initial performance of the 20-year-old group. Means and standard errors are shown for the average initial and final strength and power estimates for each age group.

10 years were tested with current isokinetic concentric elbow flexion measurements using a Kinetic Communicator (Kin-Com) model 125E dynanometer (Chattex Corp., Chattanooga, TN) (unpublished analysis). The correlation between the two measurements was $r = .71$ with the relationship expressed as:

isokinetic concentric biceps strength (newtons)
= –66.0 + 2.24*isometric arm strength (kg).

For comparison, the correlation between the isokinetic concentric elbow flexion measurement and isokinetic concentric elbow extension measurement at the same sitting was $r = .65$. Thus, the isometric measurements used in this study can be directly related to currently accepted measurements of upper body strength. On the other hand, the power measurements are harder to compare with current methods and need to be interpreted with that understanding.

Bassey and colleagues (Bassey and Short, 1990; Bassey et al., 1992) found that the differences in explosive leg power with age are far greater than those in strength. With arm strength, we found a less dramatic age difference than Bassey et al., most likely because of differences in the tasks. The 10–15 sec duration of arm cranking was different from the initial maximal power by Bassey et al., which was dependent on a rapid immediate increase in force generation. Because power is dependent on both force and velocity, any factor that affects the immediate and rapid acceleration of movement will have a maximal effect on initial power, but less of an effect over a 10–15 sec effort. The rapid acceleration appears to be adversely affected by age.

Loss of muscle mass or atrophy is considered to be the primary cause of strength loss (e.g., Brooks and Faulkner, 1994), whereas the greater loss of power is dependent on changes in strength as well as other factors. The path analysis demonstrated the expected strong relationship between strength and power. Muscle mass and body size had a greater direct effect on strength than on power. Their strongest effects on power were through strength in both genders. In addition, age was an independent contributor to losses in strength and power after controlling for height, weight, caloric expenditure, muscle mass, and gender. Unmeasured factors contributed to the persistence of the age effect in this study. Together, these observations support the conclusion that the age-associated declines in strength and power are not attributable to age-cohort differences, particularly in height, weight, and caloric expenditure.

The cause of muscle atrophy with aging is not completely understood. One possibility is that the declines result from decreasing physical activity with age. Disuse may be an important contributor, but it does not explain the losses in well trained senior athletes (Faulkner et al., 1995). Another important contributor is likely to be age-associated changes in nerve-muscle relationship including loss of spinal motor neurons and motor units (Campbell et al., 1973; Tomlinson and Irving, 1977). Reorganization of the motor units could result in a shift in the proportion of fast and slow muscle fibers with age (Larsson et al., 1979), and to changes in fiber type distribution within muscle (Lexell et al., 1983, 1986). Without a better understanding of the time course of these changes with age, the standard approach of comparing young and old subjects or animals will not determine or characterize the factors occurring early in the life span that set the age-associated course of change.

Circulatory mediators also contribute to the loss by their actions on muscle to maintain and alter homeostasis. They include hormones, growth factors, inflammatory factors, and protein synthesis activators. Age losses have been reported in growth hormone, testosterone, DHEA, and others. They appear to be general controllers responsible for maintenance as well as hypertrophy and hyperplasia of the muscle, while the neuromuscular system is responsible for the primary function of muscle, which is movement. Important hormones include growth hormone (Corpas, Harman, and Blackman, 1993), corticosteroids (Rebuffe-Scrive et al., 1988), and androgenic steroids (Gutmann et al., 1970; Krotkiewski et al., 1980). Furthermore, Phillips and colleagues (1992) have recently noted that as women go through the menopause, a dramatic decline that usually occurs in muscle strength was prevented by the use of hormone replacement. Currently there is much interest in the potential use of growth hormone to increase muscle strength in the elderly, following the report of Rudman et al. (1990). We hypothesize that in elderly frail individuals, significant losses have occurred in both hormonal and neuromuscular modulation that alter muscle and performance. What is not understood is how the two systems interact to slow or to speed deterioration of performance.

The sustained short-term power in our study was dependent on a well-coordinated turning movement in addition to strength. Power measures do not directly assess coordinated movement, but suggest that the central nervous and neuromuscular systems are changing with age, so that rapid and continuous movements are slower at any workload in older subjects. Figure 1 shows that the power generated by successively older age groups has a similar proportional decline at each load. If strength were the only factor, we would expect an interaction between age and load on power (e.g., at the lowest amp load, the effect of age-associated strength loss should be minimal and the rate of movement greatest). The figure, however, shows proportionately the same change with increasing age as with the largest amp load (4 amps). Stated differently, if force were the only important variable, then older subjects should show a proportionately greater decline in power at higher as compared with the lower amp loads. This was not observed.

With increasing age, both movement time, accuracy, and reaction time have been shown to decline in BLSA subjects (Fozard et al., 1994; Vercruyssen et al., submitted). Morgan et al. (1994) argued that the slowing results from altered motor coordination with a loss of certainty in movement. They noted that the pattern differed from what is observed in Parkinson's disease, arguing against a pathological basal ganglia process. Normal aging changes in the basal ganglia could be a contributor, as demonstrated by a continuing loss of dopaminergic neurons in the substantia nigra with increasing age leading to bradykinesia. In addition, peripheral mechanisms are likely to include slowing in peripheral nerve conduction velocities and increased muscle contraction times with age. Nerve conduction velocities decrease by 10% across the adult life span, which could increase contraction times by 5–8 msecs (Norris et al., 1953). The firing rate of the biceps brachii during maximal contraction is about 30 Hz, which could create a potential 150 to 240 msec delay during the fluid movement required to generate maximal power. We are unaware of any studies that have shown that such delays from neural firing actually adversely affect power generation.

The age-associated changes in this report did not appear to be related to serious health problems. Participation in the BLSA requires several days of testing, which is difficult for someone severely ill. The implications are that the study population and these findings reflect a relatively healthy group of individuals who have many disease processes characteristic of their age group. Specifically, we examined the length of time until death, the presence of coronary heart disease, and presence and severity of musculoskeletal problems. Only musculoskeletal problems were found to correlate to power significantly and to strength when controlling for age and sex, although correlation was very low compared with the variables examined in Figure 4. The implication is that in otherwise healthy individuals, the presence of some chronic diseases does not adversely affect their ability to maintain normal power and strength for their age.

Age differences in leg explosive power have been found to relate better to functional capability than to strength (Bassey and Short, 1990; Bassey et al., 1992). The implications are that sudden swift movements are an important component of mobility and that the greater leg power in the elderly can help to maintain better mobility and protect against falls. The relatively greater power to strength loss in the upper extremities may be an important factor in functional dependency, both directly and through coordination and strength. Williams et al. (1990) found that upper extremity performance was a predictor of functional dependency in the elderly. The Women's Health and Aging Study found that decreasing upper extremity strength was also associated with increasing disability (Ferrucci et al., 1995). As suggested by Bassey et al. (Bassey and Short, 1990; Bassey et al., 1992), upper extremity power adds another component, in addition to strength, that may be important to better define the relationship of performance to dependency.

In conclusion, the study confirms — by using long-term longitudinal data — that power changes with age to a greater extent than strength. Both power and strength began to decline by about age 40, which is younger than suggested by other studies. Limited longitudinal data in women suggested a stability in strength and power over a 4-year period. Longer longitudinal follow-up is needed, particularly in women. Both the changes in strength and power were affected by increasing age, even when considering gender, body size, and muscle mass. The independent effect of age on power argues for the importance of movement speed, coordination, and other factors in power generation.

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